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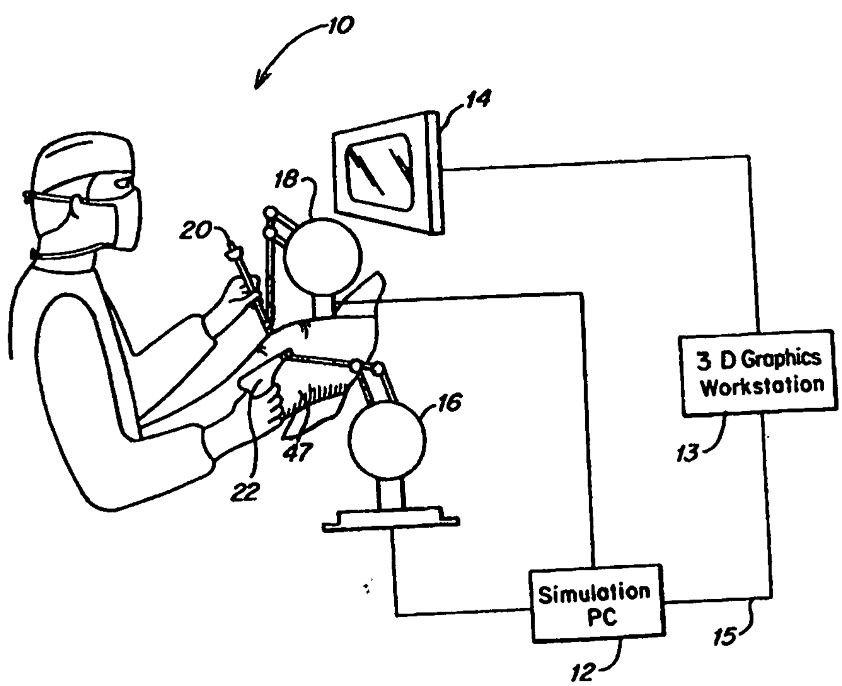
(57) Abstract



A real-time surgical simulation system includes a physical body environment, a body environment simulator and a surgical tools simulator. The physical body environment replicates a portion of a human body and includes a synthetic skin layer. The synthetic skin layer allows insertion of a surgical tool through the synthetic skin at an arbitrary location. The body environment simulator simulates a body environment within the physical body environment. The surgical tools simulator simulates at least one surgical tool within the virtual body environment that can interact with the virtual body environment, and that is coupled to a surgical tool that is manipulated by a user of the surgical simulation system. The simulated surgical tool moves corresponding to movement of the surgical tool by the user. The surgical simulation system further includes an interaction simulator that simulates interaction between the virtual body environment, components of the virtual body environment and the simulated surgical tool. This simulated interaction is provided as a three-dimensional force vector by a force feedback device, at a point on the surgical tool outside of the physical body environment. The surgical simulation system also includes a visual display device for displaying the virtual body environment, the simulated surgical tool, and the simulated interaction. With this system, there is provided an apparatus and a process for learning, practicing and experiencing dynamic, real-time, surgical procedures having a life-like feel, and laparoscopy.

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METHOD AND APPARATUS FOR SURGICAL TRAINING AND SIMULATING SURGERY

Background of the Invention

1. Field of the Invention

The invention relates generally to a computer-based simulation system of surgical procedures. In particular, the invention relates to a system for providing a realistic simulation of surgical procedures such as arthroscopy.

2. Discussion of the Related Art

Modern medicine has given rise to an increasing number of highly sophisticated surgical procedures that are performed on patients for a variety of purposes. For many of these surgical procedures, it has been the case that the only way for a practitioner to master the necessary skills and required techniques was through experience on live subjects, or animals. Live patients or animals have been essential in practicing these surgical procedures because the normal pressures, touch, sound, and relevant patient response are important, if not crucial elements of practicing successful surgical procedures. Accordingly, the tendency has been for already experienced physicians to be asked to perform whatever procedures are necessary, and it has been difficult for inexperienced physicians to obtain a desired level of competence. In addition, there is a need to maintain a high degree of skill for even experienced physicians, that is only possible through continued training. Accordingly, there is a continuing need for a substitute way of providing life-like experience without the necessity for obtaining the experience on living persons or animals.

Proposals have been made to simulate living conditions in non-living substitutes. For example, the use of computer-assisted simulation technology is becoming applicable in medicine, in part because of the high cost of traditional training resources such as live animals, physicians' time, and the like. Accordingly, the value of computer-assisted instruction has been recognized. Indeed, during the past decade, numerous medical centers have designed and used software for medical education. The software has been primarily designed to run on, for example, an IBM PC compatible and/or Macintosh computers, may include interactive capabilities with the user and allows for self-paced instruction of the user. Many of the programs also have simulations which require the user to make patient

management decisions. More recently, medical education programs have used computer graphics for instruction of a patient's anatomy. These programs provide the advantage of giving a student an opportunity to access anatomic images and related textural information, rather than spending numerous hours dissecting cadavers in a lab, and provide the additional benefit of allowing the student to spend as much time as needed to learn the material.

Although these computer-assisted programs offer many advantages in medical education, there are many limitations and drawbacks such as, for example, there is a limited scope of depicted anatomical information, and these programs do not allow for practice of actual medical procedures under realistic conditions.

One proposal that has been made to simulate living conditions in non-living substitutes is U.S. Patent No. 4,907,973, granted on March 13, 1990 to David C. Hon (hereinafter the Hon patent). Referring to Fig. 1, the Hon patent discloses a computer-based surgical simulation system 100 including a peripheral device designed to simulate a surgical instrument, as well as the involved anatomy of a patient. In particular, the Hon patent discloses in one embodiment a system for computer simulation of an endoscope examination. The Hon system includes a mock catheter 102 that is inserted within a model 104 or mock arterial path of a physical internal body part of a model. Within the model, there are a plurality of sensors (not illustrated) on the mock arterial path that track the progress of the catheter through the mock arterial path. The sensors transmit corresponding signals 105 to a computer 106 which responds to the signals by accessing stored video information in storage medium 109 representing the view which would be observed from the relative location of a tip of the catheter device. The video representation 107 is then presented by a video display 109 to the user 110 of the system of the Hon patent. In one embodiment of the system of the Hon patent, a vessel constricting simulator within the mock arterial path provides a fixed resistance to the progress of the catheter.

While the system of the Hon patent has the potential for providing a feel of a catheter device, it suffers a number of infirmities. For example, the system of Hon uses a portal for the surgical instrument that is fixed to the physical mannequin. The system of the Hon patent also lacks the flexibility to realistically simulate changes in the mock environment responsive to manipulations and performance of the surgical instrument by the operator of the system. By way of example, the system of the Hon patent does not provide for the realistic simulation of bleeding, e.g., in the event an arterial wall is punctured by the catheter, or catheter balloon

inflation and consequent removal of an occlusion within the mock arterial path. In addition, the displayed indicia representing the view from the catheter is a prestored video sequence.

Moreover, the system of the Hon patent does not provide for tracking and displaying rotation of the catheter device in the mock body environment; can only apply passive braking forces along the axis of the catheter by the constrictors along the mock arterial path and therefore cannot simulate any forces other than resistance to pushing the endoscope down the esophagus of the body such as, for example, those from a beating heart or a pulsing artery. In addition, the image representing the internal body environment cannot be modified in real-time as a result of any interaction of the catheter within the mock body environment and therefore simulation of interaction such as, for example, deformation of tissue through interaction with the catheter is not possible. The system of Hon does not have the ability to simulate interaction of the mock body environment with the surgical tools by changing the mock body environment shape, appearance, or position in response to any of poking, plucking, puncturing or incising of the mock body environment.

The Hon patent also discloses that surgical performances of the user can be recorded for evaluation, review, and comparison to other performances. However, because the system of the Hon patent suffers the infirmities discussed above, the system of the Hon patent cannot record, compare, evaluate and score performances of a user based on forces of interaction between the body environment and the surgical tools.

Another proposal for a system for providing a realistic simulation of a cardiac catheterization procedure is disclosed in international publication No. WO 96/28800, published on September 19, 1996 (the Merril disclosure). Referring to Fig. 2, the medical simulation system of the Merril disclosure includes a computer-human interface device 111 and a computer 113 storing a software program which works in conjunction with the computer-human interface device. In a preferred embodiment of the Merril disclosure, the system simulates a cardiac catheterization procedure, and the interface device is a catheter interface device that tracks the translational and rotational movement of a mock catheter 121, and provides a signal 123 to the computer program. The computer program generates a tactile feedback force signal 125 that is output to the catheter interface device to simulate resistance to the mock catheter. The computer program also provides a virtual reality simulation of movement of the catheter within the virtual catheter on a high-resolution monitor 127. The computer program can provide a variety of enhancements including 3-D imaging, narrative

audio or music via a CD-ROM 124, simulated radiopaque dye infusion, bleeding and atrial pulsation in synchronism with an on-screen EKG display.

While the Merril disclosure provides a more realistic simulation than that of the Hon system, it also suffers a number of infirmities. In particular, the system of Merril uses a portal for the surgical instrument that is fixed. Furthermore, the system of the Merril disclosure does not provide for simulated objects and tools within a virtual body environment that have their own position, orientation, space, and that can move independently in the virtual body environment. The system of the Merril disclosure does not provide for contact between any of the simulated objects and tools within the virtual body environment. Moreover, the system of the Merril disclosure does not allow for the catheter to have a position independent of the virtual body environment and that can be moved independent of the body environment.

The system of the Merril disclosure is also limited to "canned" or pre-stored simulations of simulated vessel movement, simulated catheter positioning and simulated vessel expansion in response to simulated angioplasty balloon inflation. These are precomputed responses that are not responsive to any interaction between the catheter and the simulated arterial tree. In addition, the system of the Merril disclosure can only provide restrictive forces to the mock catheter, and therefore suffers the same infirmities with respect to simulating realistic forces of the simulated surgical procedure as discussed above with respect to the Hon patent.

The surgical tools 220 employed in minimally invasive procedures such as arthroscopy and laparoscopy typically have at least four degrees of freedom (See Fig. 3). The surgical tool can move in and out of a portal 222 along a longitudinal axis 226 of the tool (axial displacement), rotate about the longitudinal axis of the tool (axial rotation) 228, and rotate about two axes 230, 232 in the plane of the body (transverse rotation). Additional degrees of freedom may include those needed for jaws or graspers of the tool. A system for simulating these interactions between a surgical tool and the body requires force feedback along one or more of these degrees of freedom. A force feedback tool such as that of the Immersion Corp., 2158 Paragon Drive, San Jose, California (Website http//:www.immerse.com) and its Laparoscopic Impulse Engine product has simulated one or more of these force interactions with motors or other force or torque producing devices that apply axial displacement forces and transverse rotation torques. In particular, the Laparoscopic Impulse Engine includes motors or force or torque producing devices, that are co-located with the portal, and requires

anchoring these devices to a physical body mock up. However, a drawback of the Laparoscopic Impulse Engine is that a motor is required on the force feedback device that is coincident with the center of rotation of the tool and that is coincident with the portal, that is used to simulate the resultant moment. Another motor that drives an axial displacement of the tool is also needed to simulate the axial force. In addition, the motor arrangements need to be anchored into the body part at a point of the portal to allow the mechanical body part to support the skin component forces of the tool. This system is therefore complex and expensive.

A Knee Arthroscopy Training System of McCarthy and Hollands (ref. McCarthy, A.D., and Hollands, R.J., "A Commercially Viable Virtual Reality Knee Arthroscopy Training System", Medicine Meets Virtual Reality, Westwood, Hoffman, Stredney, and Weghorst (Eds.), IOS Press and Ohmsha, 1998) does not use force feedback at all. Their system employs an articulated physical leg and an arthroscope. The position and orientation of the leg and scope are tracked so that corresponding computer graphic images of the view from the arthroscope can be computed. However, the lack of force feedback between the arthroscope and probe and the bones and tissues inside the leg make the system difficult to use and less than realistic.

Summary of the Invention

In view of the foregoing, it is an object of the invention to provide an improved system for simulating minimally invasive surgical procedures and for training.

According to one embodiment of the apparatus of the invention, a surgical simulation system includes a physical body environment that replicates a portion of a human body and includes a synthetic skin layer. The physical body environment is configured to allow insertion of a minimally invasive surgical tool, such as those used in arthroscopy or laparoscopy, through the synthetic skin layer into the physical body environment at an arbitrary location (the portal) selected by a user of the surgical simulation system. The surgical simulation system also includes a body environment simulator that simulates a virtual body environment within the physical body environment. The surgical simulation system also includes a surgical tool simulator that simulates a simulated surgical tool within the virtual body environment and that interacts with the virtual body environment. The simulated surgical tool is simulated at a location inside the virtual body environment corresponding to

the arbitrary location that the physical tool is inserted into the physical body environment, and is simulated so that the simulated surgical tool moves corresponding to the surgical tool that is manipulated by the user of the surgical simulation system. The surgical simulation system also includes an interaction simulator that simulates interaction between the virtual body environment and the simulated surgical tool, including any force or torque exchanged between the simulated surgical tool and the virtual body environment. The interaction simulator provides a three-dimensional (3-D) force vector at an output that represents the simulated interaction. The surgical simulation system also includes a force feedback device that applies the 3-D force vector at a point on the surgical tool outside of the physical body environment and separate from the portal. The surgical simulation system also includes a visual display that displays the virtual body environment, the simulated surgical tool, and the simulated interaction between the virtual body environment and the simulated surgical tool. With this arrangement, a realistic simulated surgical procedure is provided to the user to learn, practice, and experience various minimally invasive surgical procedures.

A preferred embodiment of the surgical simulation system also includes a resilient sheet material disposed beneath the synthetic skin layer. With this arrangement, the portal plays the role of a stable pivot, forcing the tool to rotate about the pivot when appropriate transverse rotation forces are provided by the force feedback device. This arrangement obviates the need for a motor or torque source to be located at the pivot point.

The preferred embodiment of the surgical simulation system further includes a perspective determining device that determines a position of the simulated surgical tool with respect to the virtual body environment and provides to the visual display device, information for displaying the virtual body environment and the simulated surgical tool from a perspective of the physical tool within the physical body environment.

According to one embodiment of a method of simulating minimally invasive surgery according to the invention, the method comprises the steps providing a physical body environment that replicates a portion of a human body, simulating a virtual body environment within the physical body environment, simulating a surgical tool within the virtual body environment, simulating interaction between the virtual body environment and the simulated surgical tool, and displaying the virtual body environment, the simulated surgical tool and the simulated interaction. The physical body environment is provided to allow insertion of a surgical tool through a synthetic skin layer into the physical body environment at an arbitrary

location selected by a user. In addition, the simulated surgical tool is simulated at a location inside the virtual body environment that corresponds to the arbitrary location, and is simulated to move corresponding to the surgical tool as it is manipulated by the user. In addition, the step of simulating the interaction between the virtual body environment and the simulated surgical tool includes providing any force or torque exchanged between the simulated surgical tool and the virtual body environment as a three-dimensional force vector to the surgical tool at a point outside of the physical body environment. With this method, a realistic simulated surgical procedure is provided to the user to learn, practice, and experience various minimally invasive surgical procedures.

A preferred embodiment of the step of providing the physical body environment includes providing the physical body environment with a resilient sheet material beneath the synthetic skin layer. The resilient sheet material facilitates the use of the portal as a stable pivot which the surgical tool rotates about when the three-dimensional force vector is applied to the surgical tool. With this method, there is no need for a motor or torque producing device to be located at the stable pivot point.

In addition, the preferred embodiment of the method preferably includes a step of determining a position of the simulated surgical tool with respect to the virtual body environment, and displaying the virtual body environment and the simulated surgical tool from a perspective of the surgical tool inserted into the physical body environment.

Brief Description of the Drawings

Other objects and features of the present invention will become apparent from the following detailed description when taken in connection with the following drawings. It is to be understood that the drawings are for the purpose of illustration only and are not intended as a definition of the limits of the invention. The foregoing and other objects and advantages of the invention will become more clear with reference to the following detailed description of the drawings, in which like elements have been given like reference characters, and in which:

Fig. 1 illustrates a computer-based surgical simulation system according to the prior art;

Fig. 2 illustrates another embodiment of a surgical simulation system according to the prior art;

Fig. 3 illustrates typical degrees of freedom involved in minimally invasive surgical procedures;

Fig. 4 illustrates a preferred embodiment of a surgical simulation system of the invention;

Fig. 5 illustrates a perspective view of the mechanical leg of the surgical simulation system of Fig. 4;

Fig. 6 illustrates a frequently used position of the mechanical leg of Fig. 5;

Fig. 7 illustrates an underlying sheet and top layer making up synthetic skin of the mechanical leg of Fig. 5;

Fig. 8 illustrates a view from the arthroscopic tool of the virtual body environment;

Fig. 9 is a flow diagram of a surgical skill evaluation method of the surgical simulation system of Fig. 4;

Fig. 10 illustrates an embodiment of a surgical skill evaluation module of the surgical simulation system of the invention;

Fig. 11 illustrates a method of evaluating a user's overall performance of a simulated task with the surgical simulation system of the invention;

Fig. 12 illustrates a method of measuring any surface damage to the virtual body environment by a user of the surgical simulation system of the invention;

Fig. 13 is a block diagram of an embodiment of a processor of the surgical simulation system of the invention;

Fig. 14 is a block diagram of an embodiment of a 3-D graphic simulator within the surgical simulation system of the invention;

Fig. 15 illustrates multiple forces that result from a surgical tool being placed through a portal in a skin of a body and that interact with the organs, tissues and the like of the body;

Fig. 16 illustrates how the simulated interaction forces according to the invention, are decomposed into one component along the axis of the tool and another component that is transverse to the axis of the tool.

Fig. 17A illustrates a cross-sectional view of deformation of a simulated body object according to a deformation module of the surgical simulation system of the invention;

Fig. 17B illustrates a perspective view of the deformed body object of Fig. 17A;

Fig. 18 is a block diagram of an embodiment of a dynamic simulator within the surgical simulation system of the invention; and

Fig. 19 illustrates a method of movement modeling by the surgical simulation system of the invention.

Detailed Description

The method and apparatus of the invention may be used, for example, as a surgical training simulator for minimally invasive orthopaedic surgery and, as will be described below, includes a jointed mechanical body part and a computer-based simulator that in concert emulate the surgical tools and the virtual body environment of the minimally invasive surgery. Although the preferred example to be described below will be that of arthroscopic surgery, it is to be appreciated that this method and apparatus can be used for any minimally invasive surgery. It is to be understood that for this application, an active force-feedback device is a device that provides forces to surgical tools connected to the active force-feedback device.

A preferred embodiment of a surgical simulation system 10 of the invention is illustrated in Fig. 4. The surgical simulation system includes several elements that work in concert including: a simulation processor 12 such as, for example, a personal computer, a graphics processor 13 and a display 14 such as, for example, an Octane computer graphics workstation and monitor made by Silicon Graphics, Inc.; a computer communications network 15 connecting the two processors, such as, for example, an ethernet; a jointed mechanical body part 47, force-feedback devices 16, 18, manufactured by, for example, SensAble Technologies of Cambridge, Massachusetts that provide active force feedback; and surgical tools 20, 22 such as, for example, an arthroscope and arthroscopic probe. It is to be appreciated that the simulation processor and computer graphics processor can exist in either multiple distinct computers as described above, in one computer with multiple processors or even in a single computer processor. It is also to be appreciated that although an arthroscope and probe are illustrated as the surgical tools, any surgical tools are within the scope of the invention and can include, for example, those used in laparoscopic surgery.

Referring to Fig. 5, in the preferred embodiment, the mechanical body environment 47 is a leg comprised of a universal joint 191 simulating a hip joint, a rigid link 192 covered with flesh-like synthetic material to serve as a thigh, a knee joint 193, a shaped rigid shell that serves as a supporting underlying surface of the knee, and a rigid link covered with flesh-like synthetic material to serve as a lower leg and foot 195. Sensors (not illustrated) attached to each of three rotational axes of the hip joint and the single rotational axis of the knee joint

measure the orientation of the thigh and lower leg with respect to a fixed reference platform. The leg can be moved and manipulated by the hands of the user in the normal ways a human leg is manipulated during a typical arthroscopic examination. This manipulation is used as an integral part of the simulated examination to reveal places otherwise hidden from view by the simulated arthroscopic camera during a simulated examination.

In particular, the mechanical leg 47 can be positioned into the position illustrated in Fig. 6, and that is frequently used to apply stresses to the knee in order to open up lateral compartments in the leg. The knee joint 193 is hollow in the place the arthroscopic tools 20, 22 are to be placed. The rigid shell in the shape of the knee serves as an exoskeleton type structure that maintains the exterior appearance and feel of the knee. It is covered with a fleshy material that will be described in detail below. While this shell is rigid, it can be punctured in arbitrary locations with the typical surgical tools in order to create a portal for insertion of the surgical tools. The knee exoskeleton is also strong so that it can support transverse forces that will be applied to it by the force feedback device 18 via the surgical tool 20 in order to create simulated forces of interaction between the surgical tool and the virtual body environment. The sensors (not illustrated) attached to each rotational joint (hip and knee) are used to determine the position and orientation of simulated anatomical structures inside the knee during the simulated surgical procedure. Additional force sensors (not illustrated) attached to the leg sense the application of varus and valgus forces to the leg by the user during an examination. These forces are sensed and the information is used by the surgical simulation system to reposition the simulated anatomical structures inside the knee in a realistic manner as a result of the user applied forces.

The mechanical body part 47 is provided to look, feel, and move like a human leg. Referring to Fig. 7, in a preferred embodiment, the mechanical leg is covered with a synthetic skin 212. It is to be appreciated that although the mechanical leg is used for this preferred embodiment of the invention, that a mock-up of any body part can be provided and is intended to be within the scope of this invention. The interior of the mechanical leg is hollow in areas a physician would normally place the arthroscopic tools. In this way, the tools when inserted through a portal 210 in the leg are free to move in an unobstructed way inside the mechanical leg. The mechanical leg can be manipulated by the user's hands in the normal way an orthopedic surgeon would handle a human patient's leg during an orthopedic surgical procedure such as, for example, flexing or extending the knee or hip, abducting or adducting

the hip, external or internal rotating of the hip, and application of varus or valgus forces to reveal certain internal regions of the knee during an examination.

The skin of the mechanical leg 47 includes a resilient sheet 214 made of a layer of reinforced nylon underneath a more compliant skin-like surface 212 made of a compliant layer of silicon. With the mechanical leg 47 of the present invention, it is possible for the user to make an arbitrary portal 210 in the skin 212 and sheet 214 when inserting the surgical tool 20 into the mechanical leg. The underlying sheet is drawn tight so it can provide lateral support to the surgical tool when the surgical tool is positioned through the sheet, thereby allowing the surgical tool to rotate easily about the point of intersection 216 (the pivot) with the sheet, when forces 217, 218 transverse to the longitudinal axis 215 of the surgical tool are applied at some distance from the pivot. The sheet provides the supportive pivot to the surgical tool, which is important for emulating forces of interaction between simulated objects inside the mechanical leg and the surgical tools. With the resilient sheet underneath the more compliant skin-like surface, the surgical tool can move in and out of the portal along the longitudinal axis 215 of the surgical tool (axial displacement) in response to an axial displacement force 219, rotate about the longitudinal axis of the surgical tool (axial rotation 221), and rotate 227, 229 about corresponding axes 223, 225 in the plane of the synthetic skin at the pivot point of intersection with the surgical tool. However, the tool cannot easily translate at the point of intersection with the arbitrarily placed portal due to the resistance of the sheet. This is also important for simulating the interaction between the simulated surgical tool and the mechanical leg.

Referring to Fig. 8, there is illustrated a view that the user would see from the arthroscope tool 20 of the simulation system of the invention. In particular, Fig. 8 illustrates one view of a femoral condyle 60 and a tibia 62 from the perspective of the arthroscope. The user of the simulation system views the inside of the knee through the arthroscope after inserting the arthroscope at an arbitrary portal 210 into the mechanical leg 47 (see Figs. 6-7), as discussed above. Any interaction forces between the arthroscope (not illustrated) and the virtual body part are felt by the user with the surgical tools and by a 3-D force feedback vector (to be discussed *infra*) applied through the force feedback device. As will be discussed in detail below, these forces of interaction between the simulated surgical tool and the virtual body environment are calculated by a simulation processor (see Fig. 4) and conveyed to the user through the surgical tool by the force feedback device 16. In addition, the visual image

of the virtual body environment is determined by the graphics processor 13 and displayed to the user via the 3-D graphics display 14. Accordingly, the surgical simulation system allows the user to practice, for example, the surgical procedure of arthroscopy. It is to be appreciated that although Fig. 8 illustrates a virtual knee environment, the invention is not to be limited to arthroscopy and can include any surgical procedure such as, for example, laparoscopy, and that all such surgical procedures are intended to be within the scope of the term simulated surgical procedure, as defined by this invention.

As will be described in further detail below, it is an advantage of the present invention that it is possible for the user to arbitrarily choose and change the portal 210 (see Fig. 6) for insertion of the minimally invasive surgical tool 20 into the mechanical leg 47. This functionality makes it possible to easily experiment with the effect of different portal sites. This is important, for example, when the user is creating a portal site with an incision as opposed to using a natural orifice of the body. In this manner, the choice of a correct place for incision of the surgical tool is one of the skills that a user of the system of the invention can experiment with and learn. This is one advantage of the present invention over the related art discussed *supra*, which requires a fixed instrumented portal to provide the instrumentation and force feedback required for simulation.

Referring again to Fig. 6, the active force feedback device 18 coupled to the respective surgical tools 20 applies forces having a magnitude and direction provided as a three-dimensional (3-D) force vector, provided by an interaction simulator (to be discussed *infra*), at a point of attachment 211 of the force feedback device to the surgical tool. This point of attachment is outside of the mechanical body part 47 thus enabling the tool to be extracted from the physical body environment completely, moved about freely, then inserted into another portal 210 of the user's choice all the while remaining attached to the force feedback device. This is an advantage over the related art discussed above, which requires tools and portals that are fixed relative to the physical body environment. Each force-feedback device 16, 18 (see Fig. 4) in coordination with sensors (not illustrated) that interface with the surgical tools 20, 22, also measures a position, orientation and configuration of the surgical tools. As will be described in greater detail below, the processor 12 simulates the simulated surgical tools within the virtual body environment (see Fig. 8). The simulated surgical tools have a position, orientation and movement that corresponds to the surgical tools. In addition, the forces applied to the surgical tool by the force feedback devices are used to simulate forces of

interaction between the simulated surgical tool and the virtual body environment which are also displayed on the 3-D display 14. With this system, a user of the system holding and manipulating the surgical tools will feel forces through the surgical tools that simulate the forces the user would feel if the tool were being used in a surgical procedure.

Referring again to Fig. 4, as will also be discussed in greater detail below, the simulation processor 12 includes a dynamic simulator 78 (see Fig. 13) of the virtual body environment inside the mechanical body part, including, for example, bones, joints, body tissues, ligaments, cartilage, and muscle tissues that are typical in an arthroscopic procedure. The dynamic simulator also simulates the virtual body environment to correspond to movement of the mechanical body part. The dynamic simulator may be, for example, custom C and C++ Software running at 500-1000 Hz on the personal computer, that provides a realistic simulation of the body environment. The surgical simulation system detects contact between and simulates forces of interaction between the simulated surgical tools, and between the simulated surgical tools and the virtual body environment, and simulates the movement of the virtual body environment or elements of the body environment in response to the interaction forces.

The computer graphics processor 13 or the simulation processor 12 includes a 3-D graphics simulator 74 (see Fig. 13). The graphics simulator may be, for example, custom C and C++ and Open GL Software running at 20-30 Hz. The graphics display 14 portrays a computer graphic image of the virtual body environment and surgical tools. The virtual body environment and surgical tools portrayed by the surgical simulation system can be displayed in either 3-D or two-dimensional (2-D) formats and, as will be discussed in greater detail below, can be simulated from any viewpoint, including the viewpoint of the surgeon's perspective or a viewpoint of, for example, an arthroscopic camera inserted into the simulated surgical environment. Moreover, photographic texture mapping and realistic deformable 3-D geometric models may also be used to make the images realistic and to show the effect of forces of interaction such as, for example, tissue deformation.

The surgical simulation system 10 simulates forces of interaction between the virtual body environment inside the mechanical body environment 47 and the surgical tools 20, 22, and forces resulting from movement of the mechanical body environment. The active force feedback devices 16, 18 provide interactive force-feedback with the surgical tools. The force feedback devices measure a position and orientation of the surgical tools 20, 22 attached to the

respective force feedback devices, and provide that information to the processor 12. As will be discussed in greater detail below, the simulation processor uses the position, orientation, and tool configuration information from the active force feedback device and surgical tool sensors to determine the position and orientation of the simulated surgical tools in the virtual body environment. This information is combined with position and orientation information of the virtual body environment to detect contact between the simulated surgical tools and the virtual body environment, and to compute the 3-D force vector to be applied by the force feedback devices. This 3-D force vector information is applied by the force feedback devices 16, 18 to the surgical tools.

The force-feedback devices 16, 18 when combined with physics-based simulation by the dynamic simulator 78 (see Fig. 13) of the body environment, provide realistic constraints on manipulation of the surgical tools within the virtual body environment. Accordingly, when the user of the system touches any component of the virtual body environment with the simulated surgical tools, the user will feel it by the forces presented to the surgical tools through the active force feedback devices. Simulated forces of interaction are also applied to the elements of the virtual body environment, which respond to the forces in realistic ways as provided by the physics-based simulation of the virtual body environment in response to movement by the user of the tools 20, 22.

Moreover, as will be described in greater detail below, the dynamic simulator 78 (See Fig. 18) includes a collision detection module 86 that detects collisions between the user-controlled simulated surgical tools and the simulated components of the virtual body environment or between two or more simulated components of the body environment. The dynamic simulator also includes a contact force modeling module 88 that models the contact force between the simulated surgical tools and the components of the virtual body environment or between two or more simulated components of the virtual body environment, and provides an output to a movement modeling module 90 that models and computes the response or movement of the virtual body environment to the forces resulting from this contact. The contact forces are also applied to the surgical tools through the active force feedback devices.

With the surgical simulation system of the invention, when the user of the surgical simulation system touches any component of the virtual body environment with the simulated surgical tool, the user will feel it at the surgical tool and the computed interaction forces will

prevent the user from doing something that is not possible such as, for example, pushing the simulated surgical tool through a simulated organ without resistance. One problem with prior art surgical simulators that do not include any of active force-feedback devices, collision modeling, contact force modeling and movement modeling is that a simulated object occupying a same physical space of another simulated object will pass completely through one another as though they are not there. Therefore, an advantage of the surgical simulation system of the invention is that the surgical simulation system of the invention provides the user tangible interaction with the virtual body environment in the form of active force-feedback and visible virtual body environment movement in response to interaction forces.

Referring to Fig. 9, the simulation system processor 12 of the system 10 of the invention also includes a surgical skill evaluation module 64 (See Fig. 10) that performs a surgical skill evaluation process 61 for measuring, recording, evaluating and reporting the surgical performance of the user of the simulated surgical procedure. In particular, the measured surgical tool positions, orientations, and forces that occur during the simulated surgical procedure are monitored by this module and recorded (Step 63) in a programmable storage media associated with the system 10 of the invention. The stored information is used by the surgical skill evaluation module for determining and providing a raw score of the user's performance (Step 65) based on physical data such as, for example, time information, force information, and position, orientation information of the simulated surgical tools, the virtual body environment and the mechanical body part, which is provided to the surgical skill evaluation module on lines 122, 124, 126, 128 and 130. (See Fig. 10.) The stored information is also compared to stored performance data of a population of practitioners in the field (Step 67) with experience ranging from inexperienced to "expert", who have also performed the simulated surgical procedure. The user's performance is also compared to a theoretical ideal performance (Step 69). All of this comparison data is used to determine a percentage ranking of the user's performance (Step 71).

The raw score and percentage ranking provide detailed information to the user that is useful for evaluation of the user's knowledge and skill and which, in turn, can be used for education, training, and/or accreditation of the user of the system. In particular, as will be discussed in greater detail below, the force, position, orientation, and velocity of the surgical tools, the position and orientation of the elements of the mechanical body environment and the virtual body environment, can be used to evaluate the performance of the user. It is to be

appreciated that the output of the information to the user can be provided in a plurality of different ways such as, for example, on the visual display 14 (see Fig. 4) in a graphical format. With the surgical simulation system of the invention, the user can compare his or her performance to that of practitioners in the field including an "expert", and the information can be portrayed to the user in a plurality of different manners. Thus, the surgical simulation system of the invention can be used for education, training and accreditation of the user on a surgical procedure.

Fig. 10 illustrates an embodiment of the surgical skill evaluation module 64 of the surgical simulation system of the invention. The surgical skill evaluation module includes an arthroscopic camera navigation module 114, a surface damage measurement module 116, a damaged tissue identification module 118, a tool triangulation accuracy module 120, an accrued time measurement module 117 and a peak force measurement module 119. The surgical skill measurement module and in particular, modules 114-120 within the surgical skill measurement module, use the following information: the position and orientation of the simulated surgical tools on line 122; the position and orientation of the virtual body environment on line 124; the position and orientation of the mechanical body part on line 126; an indication of time on line 128; and the forces of interaction between the simulated surgical tools and the virtual body environment on line 130. This information is used by the arthroscopic camera navigation module to measure the ability of the user to find certain regions of anatomy in the knee with the camera, by the surface damage measurement module to measure the surface damage to the virtual body environment with the cameras, probes, or other tools, by the damaged tissue identification module to measure the ability of the user to locate and identify damaged tissue by touch, by the tool triangulation accuracy module to measure the accuracy with which the user can place a probe or other tool on a specific point inside the knee using the arthroscopic camera point of view, by the accrued time measurement module to determine the time the user takes to perform the simulated task, and by the peak force measurement module to measure the peak force applied by the user to the virtual body environment.

Fig. 11 illustrates a method performed by the arthroscopic camera navigation module 114 (See Fig. 10) for determining an ability of the user of the surgical simulation system to move the arthroscopic camera to certain regions within the mechanical knee. In particular, in Step 132, the user moves the arthroscopic camera to what is believed to be the desired

position. In Step 134, the module determines the position and orientation of the camera and provides the position information on line 135. The camera navigation module compares the position and orientation of the camera, provided on line 135, with the position of the virtual anatomy provided on line 124 (Step 148) to determine a relative position of the camera to the virtual anatomy, which is provided on line 149. Certain preferred camera positions for viewing certain anatomical structures have been pre-computed, stored in memory, and are supplied on line 151. These preferred positions are compared to the relative position of the camera on line 149, to determine a distance error between the relative position of the camera and the preferred position (Step 152), which is provided as an output on line 154. A component of the user's overall score is based upon this comparison result.

Another component of the user's overall score is based on the distance the tip of the camera travels in moving to the relative viewing position. In particular, the arthroscopic camera navigation module measures the distance the camera is moved by the user to the relative position (Step 156). In general, if the tool is moved directly to the relative position, then the distance traveled by the tip of the camera is minimized and this component of the user's overall score is maximized. In contrast, if the user is less proficient with his or her movement of the tool by wandering around with the tool, the distance traveled by the camera is increased and this component of the user's overall score is lower. The distance traveled is provided on line 161.

Another component of the user's overall score is the total accrued time it takes the user to perform the simulated task. The arthroscopic camera navigation module measures the total time the user takes to move the camera to the relative position (Step 158). Accordingly, if the tool is moved directly to the desired position, then the total time is minimized thereby maximizing this component of the user's overall score. In contrast, if the camera is not moved directly to the relative position, then the overall time is increased and this component of the user's overall score is lowered. The total time is provided by the arthroscopic camera navigation module on line 163. The distance error on line 154, the total distance traveled on line 161, and the total time on line 163 are then multiplied by corresponding scaling factors (Steps 160, 162, and 164) and summed (Step 165) to provide an overall score of the user on line 167.

The tool triangulation accuracy module 120 (see Fig. 10) uses similar steps as the camera navigation module to determine the ability of the user to visually guide the tool to a

given target within the virtual anatomy, using the arthroscopic camera for navigation. In particular, the user's overall score is based upon a relative tool position to certain pre-computed tool positions, a distance traveled by the tool, and the total time it takes the user to perform the simulated task. Therefore, the tool triangulation accuracy module includes all the same steps that are used by the method of the arthroscopic camera navigation module, wherein the user is asked to touch certain target objects in the knee with the surgical tool, while maintaining the camera viewpoint with the simulated arthroscopic camera. As discussed with respect to Fig. 11, the position and orientation of the tool is measured and compared to the preferred tool position to determine an overall target distance error (Steps 134-152). In addition, the total distance moved by the tool is measured (Step 156), and the total time to perform the task are measured (Step 158) and provided on lines 161 and 163. As discussed above with respect to Fig. 11, each of the distance error, the total distance, and the total time are multiplied by scaling factors (Steps 160, 162, and 164) and summed (Step 165) to yield an overall user's score on line 167.

The damaged tissue identification module 118 (see Fig. 10) also includes some of the steps as illustrated in Fig. 11. In particular, the system of the invention simulates damaged tissue that looks normal but may have different tactile properties such as, for example, being softer or less compliant than that of healthy tissue. The user of the system can therefore only find the damaged tissue by feeling it. Therefore, the user of the system moves the surgical tool until the damaged tissue is found (Step 132) and then by, for example, pushing a button or squeezing a trigger on the surgical tool, the damaged tissue identification module measures the relative position of the tool with respect to the virtual body environment, compares the relative position of the tool to the preferred damaged tissue position (Steps 134-152), and outputs an error distance on line 154. A component of the user's overall score is based on this overall error distance. As illustrated above with respect to Fig. 11, other components of the user's overall score may be the total distance traveled by the user to locate the damaged areas and the total time accrued to perform the task. Still another component of the user's overall score that was not discussed above with respect to Fig. 11 may be whether the user found all of the damaged area. In particular, the damaged tissue areas located by the user can be compared with all of the preferred damaged tissue areas to determine whether all have been found, and this can also be a component of the user's total overall score.

Referring now to Fig. 12, there is illustrated a method performed by the surface damage measurement module 116 (see Fig. 10) of determining any surface damage to the virtual anatomy by the user performing the simulated surgical procedure. It is desirable to minimize the contact and potential damage to the bones and tissues in the knee that may be made through contact with the camera, probe, or other tools. The surface damage to the virtual anatomy is measured from the number of contacts made between the simulated surgical tools and the virtual anatomy and from the information indicating the forces exerted by the user contacting the virtual anatomy. In particular, the surface damage measurement module determines the interaction forces between the simulated surgical tools and the virtual anatomy (Step 138) from the above-identified information. The force is multiplied by the interval of time over which the force is applied (Step 144), and the total is summed for a length of time the tool is in contact with the anatomy (Step 146), to determine an overall surface damage to the simulated surgical tube.

For each of the above measurement modules 114-120, these quantities of error or scores can be compared to a database of surgical skill scores to assess how the user's skill compares to other users of the system. It is to be appreciated that although the above description with respect to Figs. 10-12 illustrates a surgical testing procedure for the procedure of arthroscopy, the invention is not to be limited to arthroscopy and can include any surgical procedure, and that all surgical procedures are intended to be within the scope of this invention. It is to be appreciated that access to detailed simulated physical measurements of the interaction between the simulated surgical tools and the virtual body environment for purposes of assessing skill of the user is an advantage of the present invention over the related art that do not include, for example, dynamic simulation that allows detailed position, velocity, and force information of the virtual body environment and simulated surgical tools.

Referring now to Fig. 13, an embodiment of the simulation processor 12 of the surgical simulation system of Fig. 4 is illustrated. The processor includes a main memory 66 including a database for holding system data and/or data that may be provided by users of the system. For example, the data may be provided by users to the surgical simulation system via a keyboard (not illustrated) or by any other input device known in the art. The main memory may also include the stored performance data discussed above. A secondary memory 68 may also be provided for maintaining the integrity of the database of the system. The simulation processor 12 also includes a controller 70 for reading and writing of data from the database

stored in the main memory and that controls the overall operation of the surgical simulation system and each of the modules to be described below. The processor further includes a display controller 72 that controls display of the simulated surgical tools and the virtual body environment on the 3-D graphics display 14 (see Fig. 4). Moreover, the processor may include: a 3-D graphics simulator 74 that renders, in real-time, a texture mapped virtual body environment and the simulated surgical tools or the 3-D graphics simulator may be part of a separate 3-D graphics workstation 13 (see Fig. 4). The processor further includes a force feedback interacter 76 that applies forces to the surgical tools 20, 22 via the force feedback devices 16, 18 (see Figure 3); and the dynamic simulator 78 that simulates interaction of the virtual body environment and the simulated surgical tools, as will be described in greater detail below.

Referring now to Fig. 14, an embodiment of the 3-D graphics simulator 74 is illustrated. The 3-D graphics simulator includes a 3-D object modeler 80 that includes 3-D object models of any of bones, joints, body tissues, organs, cartilage, muscle tissues of the virtual body environment, as well as 3-D object models of the surgical tools. The 3-D object models include geometry used for visual display that may be comprised of polygonal models, NURB models, or other computer graphic geometry modeling techniques known to those skilled in the art. The 3-D object graphical models include parameters for size, texture, geometry and topology of the simulated objects of the body environment. The 3-D graphics simulator also includes a texture mapping circuit 82 that applies texture mapping to the 3-D object models of the virtual body environment so that the virtual body environment and the components of the virtual body environment have a realistic appearance. Such texture mapping circuits are known to those of skill in the art. The 3-D graphics simulator further includes a lighting and point of view modeler 84 supporting lighting effects such as specular lighting, ambient lighting, and reflected lighting and supporting arbitrary views of the 3-D simulated environment through arbitrary positioning of the viewport. These lighting and point of view models are known to those of skill in the art. In the preferred embodiment, these lighting and point of view models are used to simulate a realistic surgical simulation of the virtual body environment, the components of the virtual body environment and the simulated surgical tools from the point of view of a simulated camera/arthroscope inserted into the mechanical leg. The point of view of the arthroscope is calculated by the 3-D graphics simulator's receipt of the position, orientation information of the body environment

on line 122, the position, location information of the surgical tool provided on line 124, and the position, orientation of the mechanical body part information provided on line 126. This information is used by the lighting, point of view module to determine perspective of the arthroscope with respect to the virtual body environment. The relative position of the arthroscope to the virtual body environment is also used to determine simulated contact forces between the simulated arthroscope and the virtual body environment as discussed below.

As was discussed above, the mechanical body part 47 (see Fig. 7) of the invention includes a resilient sheet underneath 214 a more compliant skin-like surface 212. Minimally invasive tools when inserted into a portal 210, use the portal as a pivot so that when a handle of the tool 20 is moved in one direction on the outside of the body, the tool pivots about the portal so that the tool tip on the inside of the body moves in the opposite direction. This reversal in cause and effect is one reason why minimally invasive surgery is so challenging to learn. The skin material on the mechanical leg 47 of the invention acts as such a supportive pivot for the surgical tools 20, which is important for emulating the forces of interaction between simulated objects inside the leg and the tools. The pivot is an important part of this invention for replicating forces that would be present if the tool was actually touching an object inside the leg. This pivot is also an important part of facilitating attachment of the surgical tool to the force feedback devices 16, 18 (see Fig. 4), at the part of the surgical tool 211 (see Fig. 6) that remains outside the mechanical body part, thus enabling arbitrary placement of the tool and manipulation of the surgical tool and/or mechanized leg or body part.

Referring to Fig. 15, it is illustrated that the surgical tool 20, when placed in the interior of the mechanical body environment through an arbitrary portal 210 in the synthetic skin 212, can interact with simulated organs and tissues in such a way that multiple simulated interaction forces F_{o1}, F_{o2}, and F_{o3} from the simulated organs and tissues, can be applied to the surgical tool. These simulated forces can be applied at any place on the tool including in particular, at the tip or along the shaft of the tool. A net result of these multiple interaction forces can be equivalently represented by interaction force F_{or} and a moment M_{or} about a well-defined point on the tool, such as at the portal or pivot point of intersection with the synthetic skin. Accordingly, a force feedback device that is used to mimic these multiple forces of interaction typically must produce some or all of these resulting forces and moments.

Referring now to Fig. 16, forces applied to the tool from the force feedback device must be equivalent to the interaction forces from the internal organs. It has been discovered with the present invention that these interaction forces to be simulated, can be decomposed into one component that acts along an axis of the tool F_{ora} and another component that acts transverse to the axis of the tool F_{ort}. As illustrated in Fig. 16, these interaction forces include forces from the skin F_s, including axial components F_{sa} and transverse components F_{st}. Also shown in Fig. 16 is the applied force from the force feedback device, F_{ffd}, and its components, F_{ffda} and F_{ffdt}, that is designed to emulate the interaction forces between the tool and the internal tissues. The force feedback forces are applied to the tool at the point 211 (see Fig. 6), that is some distance, L, from the pivot point.

It is a novel discovery of this invention, that the interaction forces, M_{or} and F_{ora} can be simulated with a 3-D force vector. In particular, the transverse components of the applied 3-D force vector are used to emulate the moment, M_{or}, and the axial components of the applied 3-D force vector are used to emulate the axial component, F_{or}, according to the following equations:

$$F_{ora} = F_{ffda}$$

$$M_{or} = F_{ffdt} * L$$

The role of the synthetic skin in these equations becomes apparent when we consider that the skin must support all transverse components of force according to the following force balance equation:

$$F_{ort} + F_{st} + F_{fdt} + F_{ht} = 0$$

where F_{ht} is the transverse component of force applied by the user's hand, which also is applied to the tool. Therefore, the skin must be sturdy enough to support these transverse forces without significant deformation or distortion which would decrease the fidelity of the simulated forces.

In particular, it is a novel aspect of this invention to simulate the forces of interaction between the surgical tool and the simulated objects inside the mechanical body environment with a force feedback device that need only apply a 3-D force vector to the physical tool. It is an advantage of this invention that the force feedback device need not apply a moment or torque to the physical tool. This is important according to the present invention, because force feedback devices that apply a moment to the tool at the center of rotation of the tool (the portal) may require a motor to be located at that point. This either necessitates that the motor

be fixed to the portal or that the motor be attached at the end of a linkage of the force feedback device, which significantly increases the mass, inertia, and complexity of the force feedback device and which will lower its performance. This makes the simulation of these interaction forces according to the present invention less complex.

Another advantage of the system of the present invention is that the user can arbitrarily choose and change the portal 210 (see Figs. 6-7) for insertion of the minimally invasive surgical tool. In particular, with the realization of the present invention that the multiple simulation forces can be simulated with a 3-D force vector applied to the tool at the point 211 that remains outside of the mechanical body part, and with the synthetic skin layer of the mechanical body part, the user can arbitrarily choose and change the portal for insertion of the surgical tool. This allows the user to easily experiment with the effect of different portal sites. This is especially important to the user, when the user is creating a portal site with an incision as opposed to using a natural orifice of the mechanical body part. For this situation, the choice of the correct portal location for incision is one of the skills that the user must learn. Accordingly, it is an advantage of the present invention that the appropriate choice of the portal location can be experimented with and learned according to the surgical simulation system of the invention. Therefore, it is an advantage of the surgical simulation system of the present invention that an orifice or incision into the mechanical body part does not have to be instrumented in any way. In particular, the user can arbitrarily choose it.

The 3-D graphics simulator 74 (see Fig. 14) also includes a deformation module 85 that efficiently modifies the geometry of elements of the virtual body environment in real-time to represent deformation that occurs during interaction with the simulated surgical tools or other simulated objects. The deformation module modifies the geometric models in the region near the application of an interaction force with the surgical tool or other element of the body environment.

In one preferred embodiment of the surface deformation module 85, this interaction force is applied at one or more points on the simulated 3-D object such as, for example, the point at which the meniscus is poked with a simulated probe. In other words, for the arthroscopic surgical procedure, the surface deformation module modifies the point on the meniscus that is touched by the surgical probe to follow the probe as the probe is pushed into the meniscus. The geometry model in the vicinity of the touch point that represents the simulated body meniscus such as, for example, the vertices of a polygonal meniscus model,

are modified according to a deformation function. As illustrated in Fig. 17A, the deformation function adjusts an undeformed vertex position 166 of the meniscus model to a deformed vertex position 171 depending upon a magnitude M of the deformation of an undeformed touch point 168 to a deformed touch point 170, and the distance d of the undeformed vertex 166 from the undeformed touch point 168. The magnitude M and the distance d are used to determine a region of deformation 172 of the meniscus, as illustrated in perspective view in Fig. 17B. This deformation module is efficient because it does not require modification of the entire surface geometry of the meniscus, and the calculations for each point are simple. This deformation function can be applied to multiple points or regions of a geometric model.

Referring now to Fig. 18, there is illustrated an embodiment of the dynamic simulator 78 of Fig. 13. The dynamic simulator provides for collision detection, simulation of the interaction forces, and movement modeling of the virtual body environment and the components of the virtual body environment. In addition, the dynamic simulator provides for collision detection and simulation of the interaction forces of the simulated surgical tools. Movement of the simulated surgical tools is determined from the measured position, orientation, and configuration information of the surgical tools mounted to the force feedback devices. The simulated components of the body environment are simulated to obey physical properties such as Newton's Laws. In particular, the simulated components of the body environment may be comprised of rigid links that are connected with flexible joints with one or more degrees of freedom. Rigid or deformable 3-D geometry may be attached to these links. When interaction forces are applied to the links of a simulated component of the body environment, the movement module computes its gross body movement and movement of its flexible joints according to Newton's Laws. As discussed above, the 3-D simulated components of the body environment have physical properties such as size, mass, and inertia according to the 3-D models. When the simulated components occupy a same physical space with each other or with the simulated surgical tools, the dynamic simulator simulates the components so they will collide and exchange interaction forces in equal and opposite directions according to Newton's Laws. Similarly, the dynamic simulator simulates the components so that when interaction forces are applied to simulated objects, they move in response to those forces according to Newton's Laws. According to the embodiment of the dynamic simulator of the invention illustrated in Fig. 18, this physically realistic behavior is

simulated with three modules: a collision detection module 86, a contact force modeling module 88 and a movement modeling module 90.

The dynamic simulator module further includes a simulated object kinematics module 91 which determines the position and orientation of any part of a simulated object from knowledge of the object's shape and the position of the object's joints or degrees of freedom. The dynamic simulator module also includes a surgical tool kinematics module 93 which determines the position and orientation of any part of a simulated surgical tool. The surgical tool kinematics model receives measurements of the position of the force feedback device on line 174, information about the structure of the force feedback device on line 176, measurements from the sensors on the surgical tools on line 178, and information about the structure of the surgical tool on line 180 to compute the position and orientation of any part of the surgical tool. While it is possible to determine the position and orientation of the surgical tools from this information, in a manner which is independent of the physical body environment, it may be desirable to use information regarding the position of the physical body environment on line 179 in order to more accurately determine the position of the tool when it is inside the physical body environment. In particular, referring to Fig. 6, it is sometimes desirable to measure the position of the portal 210 on the leg surface. The location of this point fixed to the leg can be tracked using the leg sensors (not illustrated). When the tool is inserted into the portal, it is known that the tool must pass through this point. The location of this pivot point as measured by the leg sensors and the position of the tool attachment point 211 as measured by the force feedback device 18 and provided on line 174, can be used to determine the orientation of the tool, because it is known that the tool must pass through both of these points. This approach obviates the need to use the information on lines 178, 180 from the orientation sensors (not illustrated) attached to the force feedback device, to determine the orientation of the tool when it is inserted into the knee. This measurement approach helps to eliminate measurement errors that can arise due to insufficient resolution of the orientation sensors on the force feedback device.

The collision detection module 88 detects a collision between any of two simulated body components, a simulated body component and the virtual body environment, or a simulated body component and a simulated surgical tool or two or more simulated surgical tools (hereinafter "simulated objects"). The collision detection module checks the distance between features of simulated objects to check for interpenetration of 3-D geometric

representations of two simulated objects. These collision detection techniques are generally known to those of skill in the art. If the two simulated objects are found to be interpenetrating, then the collision detection module determines the surface features of the simulated objects that are colliding and the amount of interpenetration is calculated.

When two simulated 3-D objects are found to be in contact, then the contact force modeling module 88 will compute interaction forces between the simulated objects in order to simulate interaction of the two simulated objects. In particular, equal and opposite contact forces are applied to each simulated object in accordance with Newton's Third Law. The contact force modeling module determines the interaction forces based upon the relative position and velocity of points on the surface of each simulated object. The position and velocity information is provided by the surgical tools kinematics module 93 and the simulated organ kinematics module 91. The contact forces are computed with force models that combine the relative position and velocity information with spring elements, dissipative elements, and frictional elements as is generally known to those of skill in the art. The spring elements determined by the force models are a function of the relative position of the contacting surfaces of the simulated 3-D objects. The dissipative elements are a function of relative velocity of the contacting surfaces. According to this embodiment of the dynamic simulator of the invention, the net forces due to the spring and dissipative elements are constrained to satisfy friction models such as, for example, Coulomb friction, static friction, and kinetic friction. The friction models provide for slipping of one contacting surface of a 3-D simulated object relative to another contacting surface of the other 3-D object. The friction models constrain the contact forces such that they obey certain relationships between the simulated objects. These friction models are generally known to one of skill in the art. The contact force modeling module then provides an output to the movement modeling module 90 indicating the contact forces that result from the simulated contact between the simulated objects of the virtual body environment.

The movement modeling module 90 determines movement of the simulated objects in response to forces provided by the contact force modeling module 88, that arise from contact between any of the simulated objects and/or forces due to gravity. As discussed above, the simulated objects have physical attributes such as, for example, mass, inertia, energy and momentum. Accordingly, the simulated objects move realistically in response to contact forces; this movement is determined by the movement modeling module according to

Newton's Second Law of Motion. The movement modeling module includes the physical description of the simulated objects such as each object's mass, inertia, size and its joints or degrees of freedom. The movement modeling module also includes an acceleration modeling module 92 that determines the acceleration of the simulated objects and degrees of freedom, such as, for example, translation and rotation of the simulated objects in response to the application of the above-described external forces and/or a lack of such external forces. In particular, referring to Fig. 19, there is illustrated a method of determining the movement of the simulated objects according to the invention. The movement modeling module receives the interaction force information (Step 184) from the contact force modeling module. The movement modeling module computes the acceleration (Step 186) of the simulated objects. The acceleration of objects is integrated with time to determine a velocity (Step 188) and a position (Step 190) of the simulated objects through a numerical integration process generally known to one of skill in the art.

According to the invention, a surgical simulation system and method is provided for learning, practicing, experiencing and evaluating minimally invasive surgical procedures such as arthroscopy and laparoscopy. With the method and system of the invention, the need for physical models or live patients is eliminated and a life-like simulation is provided such that the user sees and hears a life-like simulated surgical environment and dynamic situations in real-time using a mechanical body part, 3-D computer generated graphics and sound, and such that the user feels the interaction with the virtual body environment and simulated surgical tools.

A big advantage of the invention is that these minimally invasive procedures can be practiced including decisions that are necessarily learned such as, placement of the incision or portal of the minimally invasive tool.

Another advantage of the surgical simulation system and method of the invention is that it will help to improve medical education by providing a plurality of life-like surgical situations to the user to experience, practice and perfect. The system and method may be used to control and standardize training regimen. With the system and method of the invention, students can learn by practicing. In particular, students can be presented with lessons that are commensurate with their skill level and students can learn to adapt procedures for a range of anatomical variations and surgical conditions. Moreover, students will be able to repeat the simulated surgical procedures until they master them without fear of any harm to a patient.

The surgical simulation system and method of the invention also makes it possible to objectively evaluate the surgical skills of a student. The detailed information provided by the system and method such as, for example, position, velocity and force information makes it possible to measure the tool accuracy, tissue damage, and surgical techniques of the student. The students will also be able to review their performance and compare it to that of "experts" in the field who have performed the same procedure. Moreover, by using the recorded performance of the "expert" as a standard, the surgical simulation system and method of the invention further enhances the teaching capacity of experts beyond the one-to-one apprenticeship that is the standard today.

Another advantage of the surgical simulation system and method of the invention is that it can also be used with traditional training techniques to improve the quality and reduce the costs of surgical education by insuring that students are prepared to make the best possible use of valuable time that is provided to the students in the operating room.

Still other advantages of the surgical simulation system and apparatus of the invention include: surgical training can be provided without the use of human patients, hospital space or animals; the surgical simulation system and method will help develop and train the physical motor skills of the student, the perceptual tasks of the student and the cognitive decision-making of the student, and the surgical training system and method will allow medical students to practice routine procedures, encounter patients with rare medical conditions or unexpected complications and to practice techniques to handle each of these situations. Accordingly, in contrast to accepted practice where only experienced surgeons are exposed to such a wide range of conditions and complications that can occur, the surgical simulation system and method of the invention will provide a wide range of conditions and complications to any user. In addition to the training provided by the surgical simulation system and method of the invention, the system and method of the invention can also be used to assess the surgical performance of the student and play a roll in certification of the student for surgical procedures.

Having thus described at least the preferred embodiment of the invention, various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing

description is by way of example only and the invention is limited only as defined in the following claims and the equivalents thereto.

What is claimed is:

CLAIMS

1. An interactive, surgical simulation system comprising:

a physical body environment that replicates a portion of a human body and includes a synthetic skin layer, the physical body environment allowing insertion of a surgical tool through the synthetic skin layer into the physical body environment at an arbitrary location selected by a user;

a body environment simulator that simulates a virtual body environment within the physical body environment;

a surgical tool simulator that simulates a simulated surgical tool within the virtual body environment at a location inside the virtual body environment corresponding to the arbitrary location, and is simulated to move corresponding to the surgical tool that is manipulated by the user of the surgical simulation system;

an interaction simulator that simulates interaction between the virtual body environment and the simulated surgical tool including any force or torque exchanged between the simulated surgical tool and the virtual body environment, and for providing the simulated interaction as a 3-dimensional force vector;

a force feedback device attached to the surgical tool at a point outside of the physical body environment, that applies the 3-dimensional force vector corresponding to the simulated interaction, to the surgical tool at the point outside of the physical body environment; and

a visual display device for displaying the virtual body environment, the simulated surgical tool and the simulated interaction.

2. The surgical simulation system as claimed in claim 1, wherein the synthetic skin layer includes a resilient sheet material disposed beneath the synthetic skin layer, the resilient sheet material providing a stable pivot that facilitates the surgical tool rotating about the stable pivot when the three-dimensional force vector is applied to the surgical tool, and thereby eliminating the need for a motor or torque producing device to be located at the stable pivot.

3. The surgical simulation system claimed in claim 1, further comprising a perspective determining device that determines a position of the simulated surgical tool with respect to the virtual body environment, and that provides to the visual display device, information for

displaying the virtual body environment and the simulated surgical tool from a perspective of the physical tool within the physical body environment.

4. The surgical simulation system as claimed in claim 1, wherein the simulated interaction between the virtual body environment and the simulated surgical tool includes any of movement, collision and force between the virtual body environment and the simulated surgical tool in response to any of movement of the physical tool, movement of the physical body environment, or movement of the virtual body environment.

5. The surgical simulation system as claimed in claim 1, wherein the physical body environment is jointed to move like a jointed body part.

6. The surgical simulation system as claimed in claim 5, wherein the physical body environment is hollow inside the synthetic skin layer to allow movement of the physical tool within the physical body environment.

7. The surgical simulation system as claimed in claim 5, wherein the physical body environment includes sensors to measure physical forces applied to the physical body environment.

8. The surgical simulation system as claimed in claim 7, wherein the physical body environment includes additional sensors to measure a position of the jointed body environment with movement of the physical body environment; and

wherein the body environment simulator, responsive to the measured position and the measured physical forces of the jointed body environment, simulates the virtual body environment.

9. The surgical simulation system as claimed in claim 1, further comprising a 3-D graphics simulator including 3-D geometric object models and components, that simulates the virtual body environment and the simulated surgical tool within the virtual body environment in 3-D.

10. The surgical simulation system as claimed in claim 9, wherein the 3-D graphics simulator includes a texture mapping circuit that provides texture to the virtual body environment so as to represent a realistic body environment and components of the virtual body environment.

11. The surgical simulation system as claimed in claim 10, wherein the virtual body environment includes biological tissue simulated in various states of decomposition or disrepair.

12. The surgical simulation system as claimed in claim 1, wherein the body environment simulator and the surgical tool simulator include lighting models and point of view models for the perspective of the physical tool within the physical body environment.

13. The surgical simulation system as claimed in claim 1, wherein the interaction simulator includes a collision detector that determines whether any collision occurs between the simulated surgical tool and the virtual body environment.

14. The surgical simulation system as claimed in claim 13, wherein the interaction simulator further includes a contact force modeling module that determines an exchange of force between the simulated surgical tool and the virtual body environment.

15. The surgical simulation system as claimed in claim 1, wherein the interaction simulator includes a movement modeling module and a surface deformation module that determine movement and deformation of any of the simulated surgical tool and the virtual body environment, in response to any of the movement of the physical tool, the movement of the physical body environment, and the movement of the virtual body environment.

16. The surgical simulation system as claimed in claim 15, wherein the movement modeling module distorts a surface of a component of the virtual body environment to provide a deformed virtual component according to a relative position of the simulated surgical tool to the component of the virtual body environment.

17. The surgical simulation system as claimed in claim 16, wherein the movement modeling module further includes an acceleration module that determines an acceleration of the virtual body environment in response to contact between the simulated surgical tool and the virtual body environment.

18. The surgical simulation system as claimed in claim 1, further comprising a surgical skill module that records any of a surgical tool position and orientation, the virtual body environment position and orientation, interaction forces between the virtual body environment and the simulated surgical tool, an elapsed time of a simulated procedure by the user, and a total distance traveled by the surgical tool.

19. The surgical simulation system as claimed in claim 18, wherein the interaction forces include forces at the physical tool and the point of application of the force between the virtual body environment and the simulated surgical tool, as a result of the user performing the simulated medical procedure on the physical body environment.

20. The surgical simulation system as claimed in claim 18, wherein the surgical skill measurement module includes performance data of others, including idealized performance data indicative of an ideal performance of the simulated medical procedure.

21. The surgical simulation system as claimed in claim 20, wherein the surgical skill measurement module compares the performance data of others with the data of the simulated medical procedure by the user, to provide comparison data that is presented to the user.

22. The surgical simulation system as claimed in claim 21, wherein the surgical skill measurement module analyzes the comparison data to provide an assessment of the simulated surgical procedure by the user.

23. A method of simulating minimally invasive surgery, comprising the steps of:

providing a physical body environment that replicates a portion of a human body and includes a synthetic skin layer, the physical body environment allowing insertion of a surgical tool through the synthetic skin layer into the physical body environment at an arbitrary location selected by a user;

simulating a virtual body environment within the physical body environment;

simulating a simulated surgical tool within the virtual body environment, at a location inside the virtual body environment corresponding to the arbitrary location, and that moves corresponding to the surgical tool that is manipulated by the user of the surgical simulation system;

simulating interaction between the virtual body environment and the simulated surgical tool including any force or torque exchanged between the simulated surgical tool and the virtual body environment, and providing the simulated interaction as a 3-dimensional force vector;

applying the 3-dimensional force vector corresponding to the simulated interaction, to the surgical tool at a point outside of the physical body environment; and

displaying the virtual body environment, the simulated surgical tool and the simulated interaction.

24. The method as claimed in claim 23, wherein the step of providing the physical body environment includes providing a resilient sheet material disposed beneath the synthetic skin layer, the resilient sheet material providing a stable pivot that facilitates the surgical tool rotating about the stable pivot when the three-dimensional force vector is applied to the surgical tool, and thereby eliminating the need for a motor or torque producing device to be located at the stable pivot.

25. The method as claimed in claim 23, further comprising the step of determining a position of the simulated surgical tool with respect to the virtual body environment, and displaying the virtual body environment and the simulated surgical tool from a perspective of the surgical tool within the physical body environment.

26. The method as claimed in claim 23, including simulating any of movement, collision and force between the virtual body environment and the simulated surgical tool, in response to any of movement of the physical tool, movement of the physical body environment, and movement of the virtual body environment.

27. The method as claimed in claim 23, including measuring physical forces applied to the physical body environment and simulating the virtual body environment responsive to the measured physical forces.

28. The method as claimed in claim 23, including measuring a position of the jointed body environment with movement of the physical body environment and responsive to the measured position of the jointed body environment, simulating the virtual body environment.

29. The method as claimed in claim 23, further comprising simulating the virtual body environment and the simulated surgical tool within the virtual body environment in 3-D.

30. The method as claimed in claim 29, further comprising texture mapping the virtual body environment so as to represent a realistic body environment and components of the virtual body environment.

31. The method as claimed in claim 30, further comprising simulating biological tissue in various states of decomposition or disrepair.

32. The method as claimed in claim 23, further comprising applying the 3-dimensional force vector to the physical tool at a point outside the physical body environment, to simulate the forces of interaction between the physical tool and the virtual body environment within the physical body environment.

33. The method as claimed in claim 23, further comprising determining whether any collision occurs between the simulated surgical tool and the virtual body environment.

34. The method as claimed in claim 33, further comprising determining an exchange of force between the simulated surgical tool and the virtual body environment.

35. The method as claimed in claim 23, further comprising determining movement and deformation of any of the simulated surgical tool and the virtual body environment, in response to any movement of the physical tool, the movement of the physical body environment, and the movement of the virtual body environment.

36. The method as claimed in claim 35, further comprising distorting a surface of a component of the virtual body environment to provide a deformed virtual component, according to a relative position of the simulated surgical tool to the component of the virtual body environment.

37. The method as claimed in claim 36, further comprising determining an acceleration of the virtual body environment in response to contact between the simulated surgical tool and the virtual body environment.

38. The method as claimed in claim 23, further comprising recording any of a surgical tool position and orientation, the virtual body environment position and orientation, interaction forces between the virtual body environment and the simulated surgical tool, an elapsed time of a simulated procedure by the user, and a total distance traveled by the surgical tool.

39. The method as claimed in claim 38, further comprising recording the interaction forces at the physical tool and the point of application of the force between the virtual body environment and the simulated surgical tool, as a result of the user performing the simulated medical procedure on the physical body environment.

40. The method as claimed in claim 39, further comprising comparing the performance of others with the performance of the simulated medical procedure by the user.

41. The method as claimed in claim 40, further comprising analyzing the comparison data to provide an assessment of the simulated surgical procedure by the user.

42. The method as claimed in claim 25, further comprising determining whether a certain portion of the virtual body environment is within the display of the virtual body environment.

43. The method as claimed in claim 23, further comprising determining an orientation of the surgical tool when it is inserted into the physical body environment by computing the orientation of the tool from the attach point of the tool to the force feedback device and the portal location.

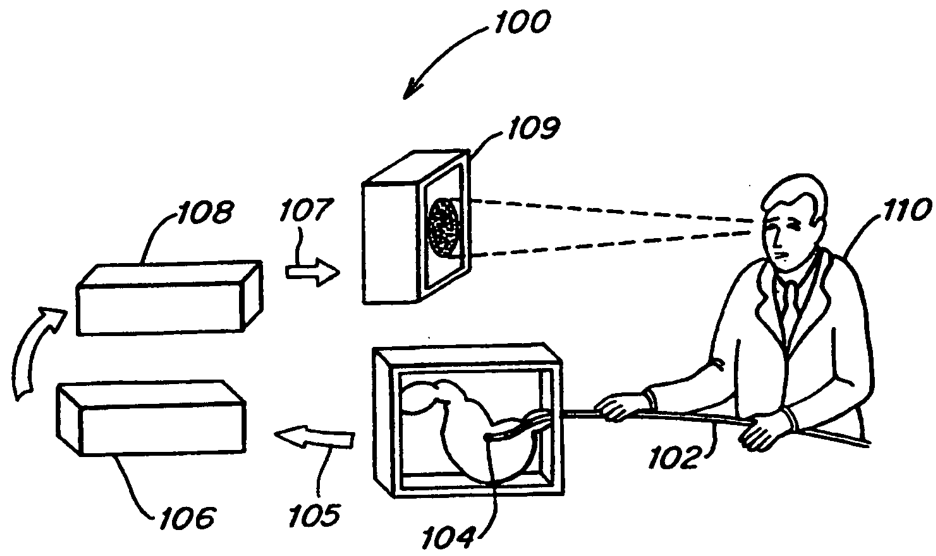

FIG. 1
(PRIOR ART)

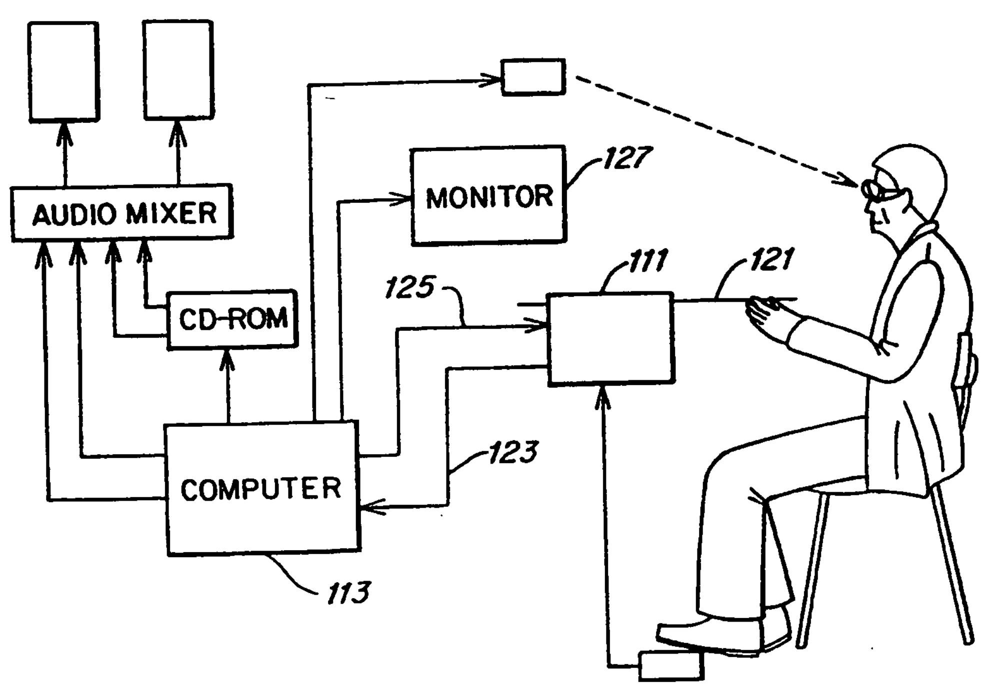

FIG. 2
(PRIOR ART)

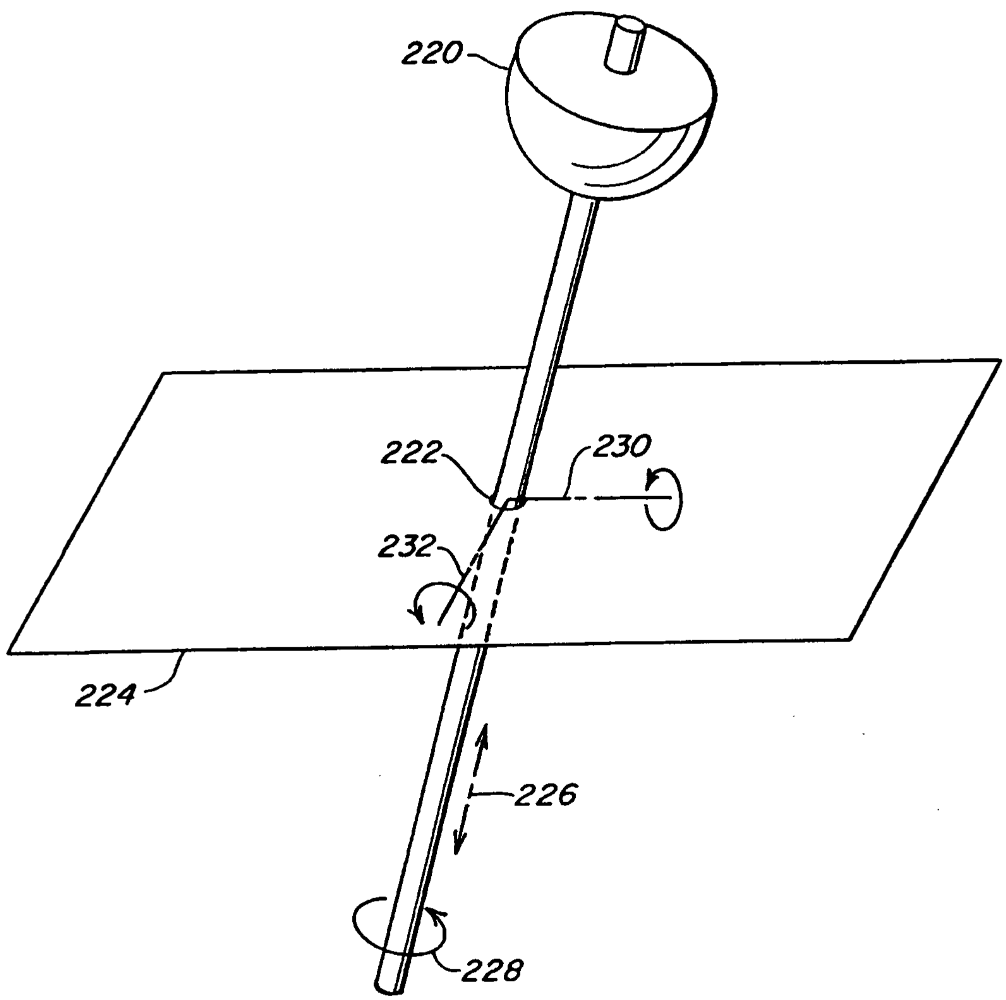

FIG. 3

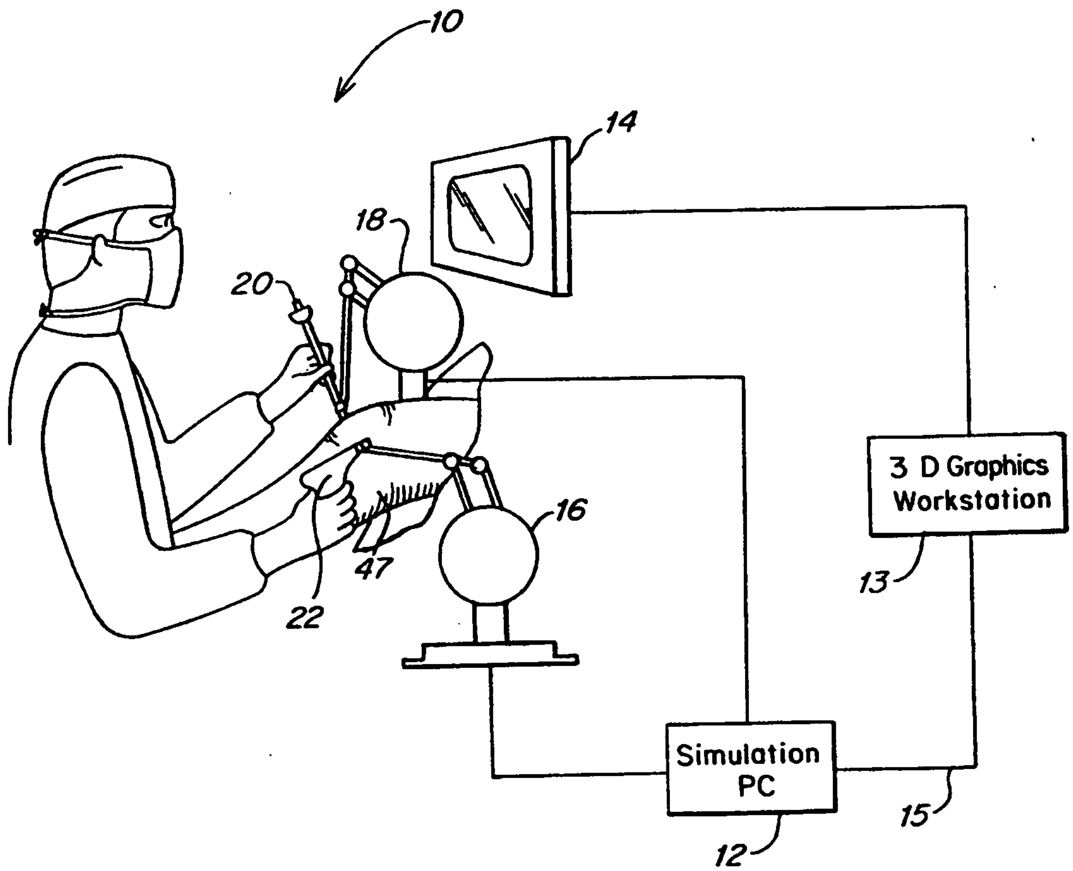
10
14
18
20
3 D Graphics Workstation
16
47
22
13
Simulation PC
15
12

FIG. 4

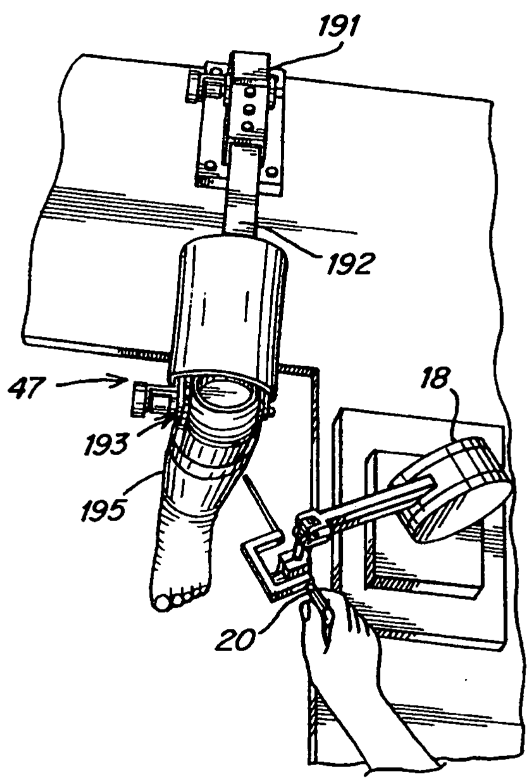

FIG. 5A

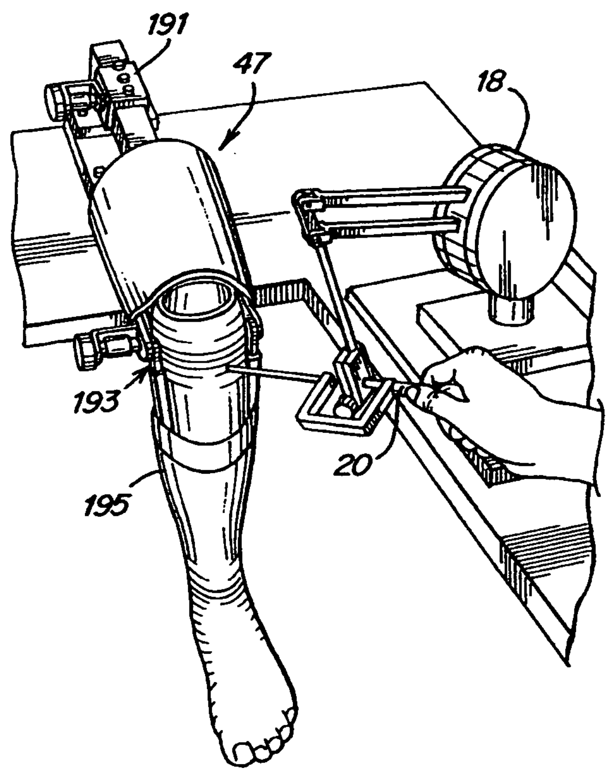

FIG. 5B

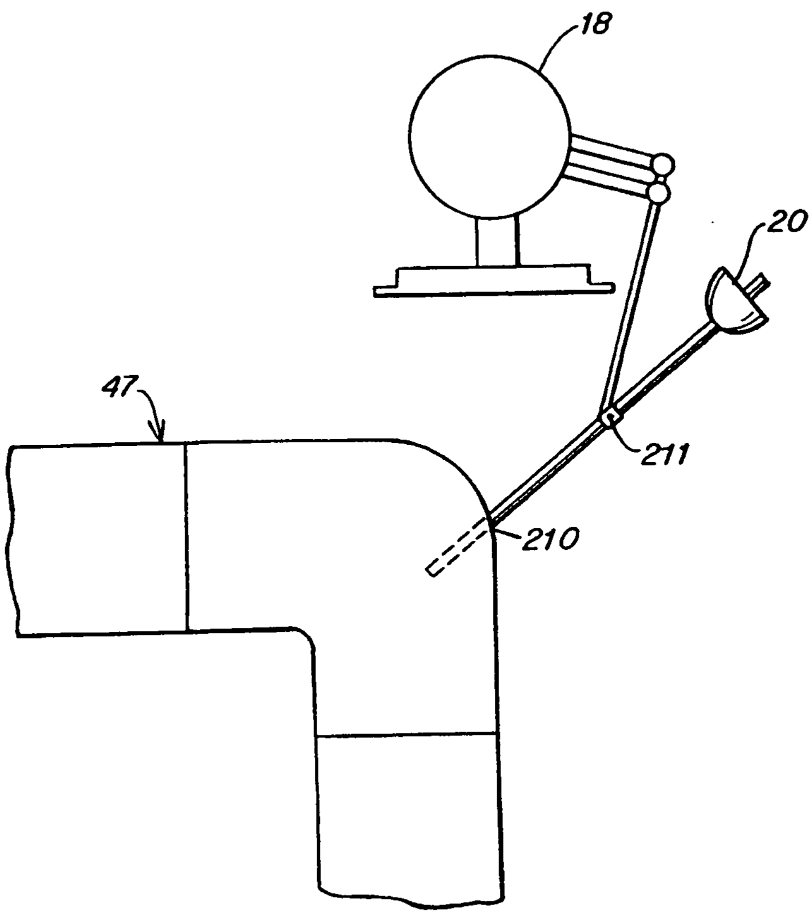

FIG. 6

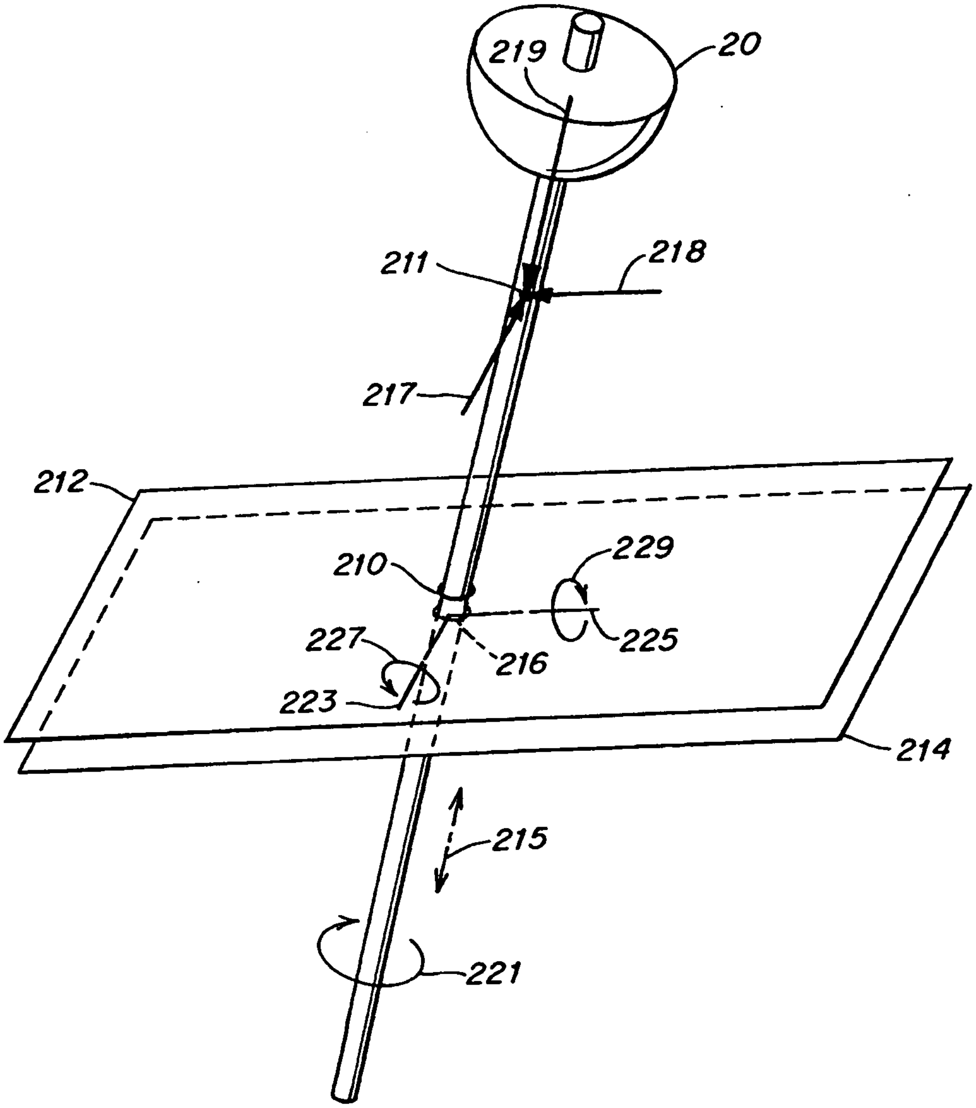

FIG. 7

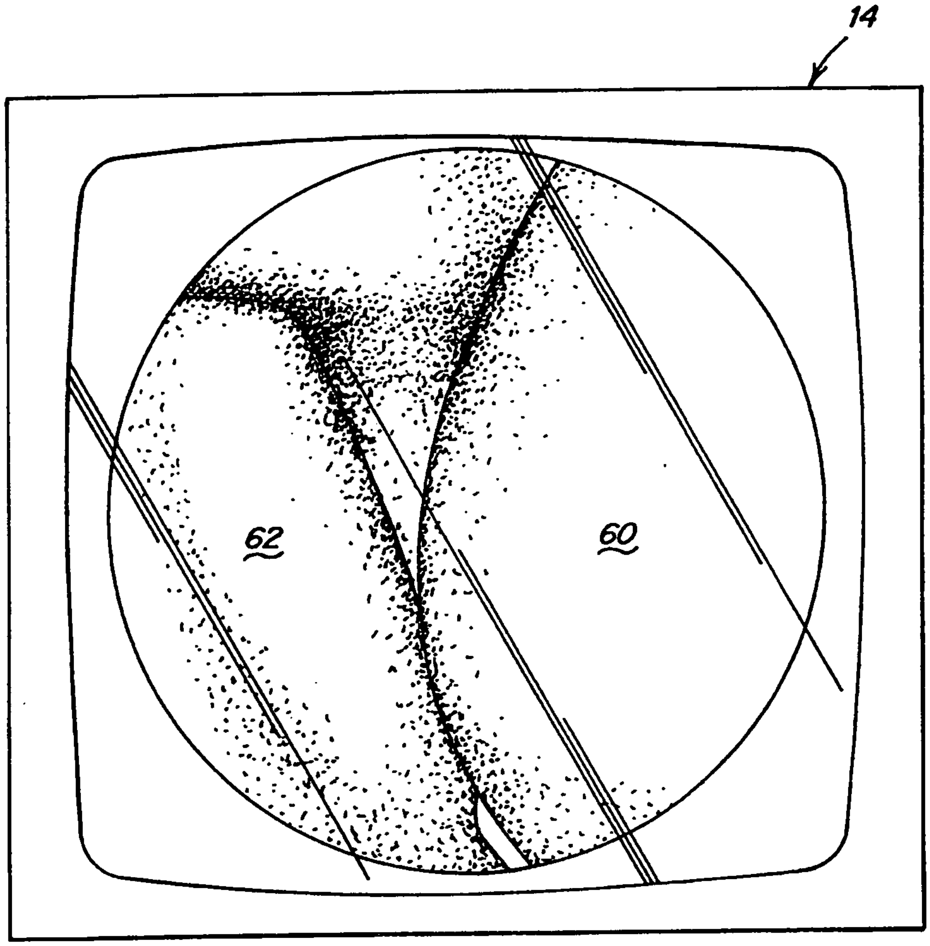

Fig. 8

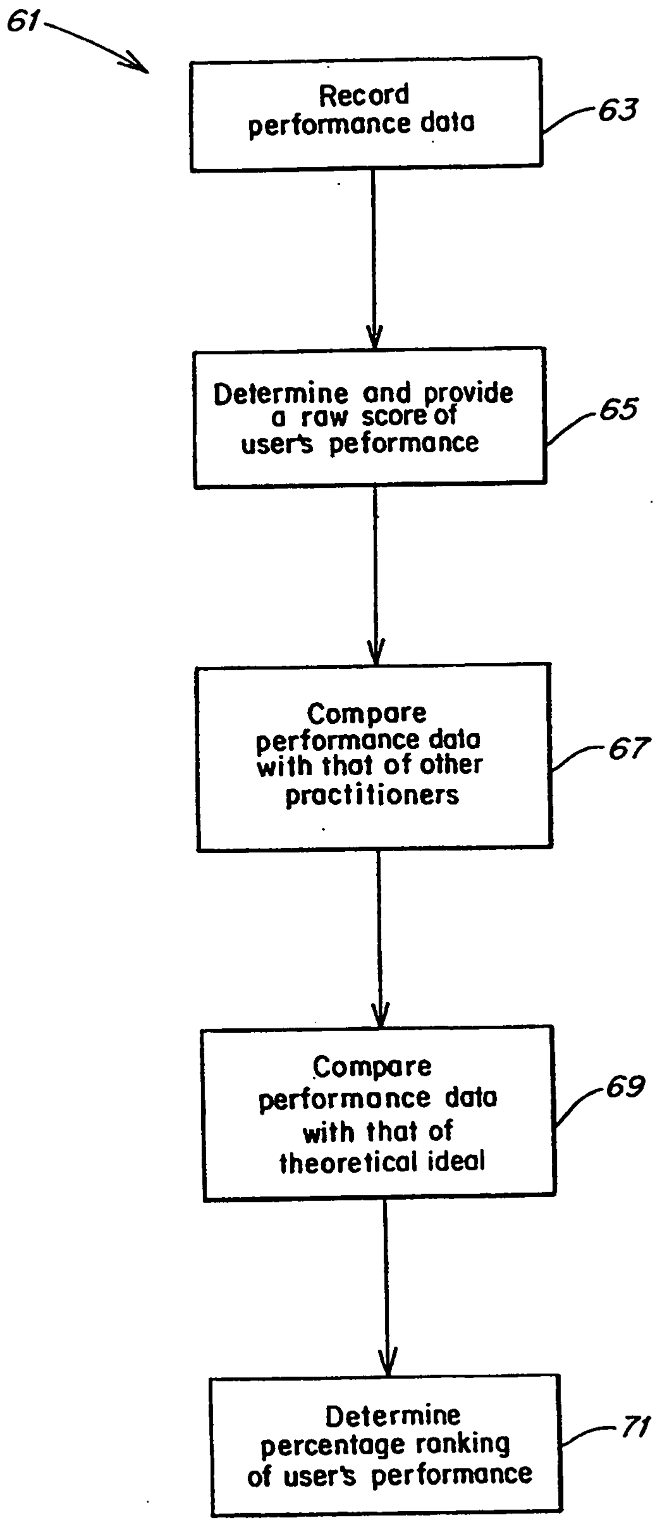
61
Record performance data
63
Determine and provide a raw score of user's peformance
65
Compare performance data with that of other practitioners
67
Compare performance data with that of theoretical ideal
69
Determine percentage ranking of user's performance
71

FIG. 9

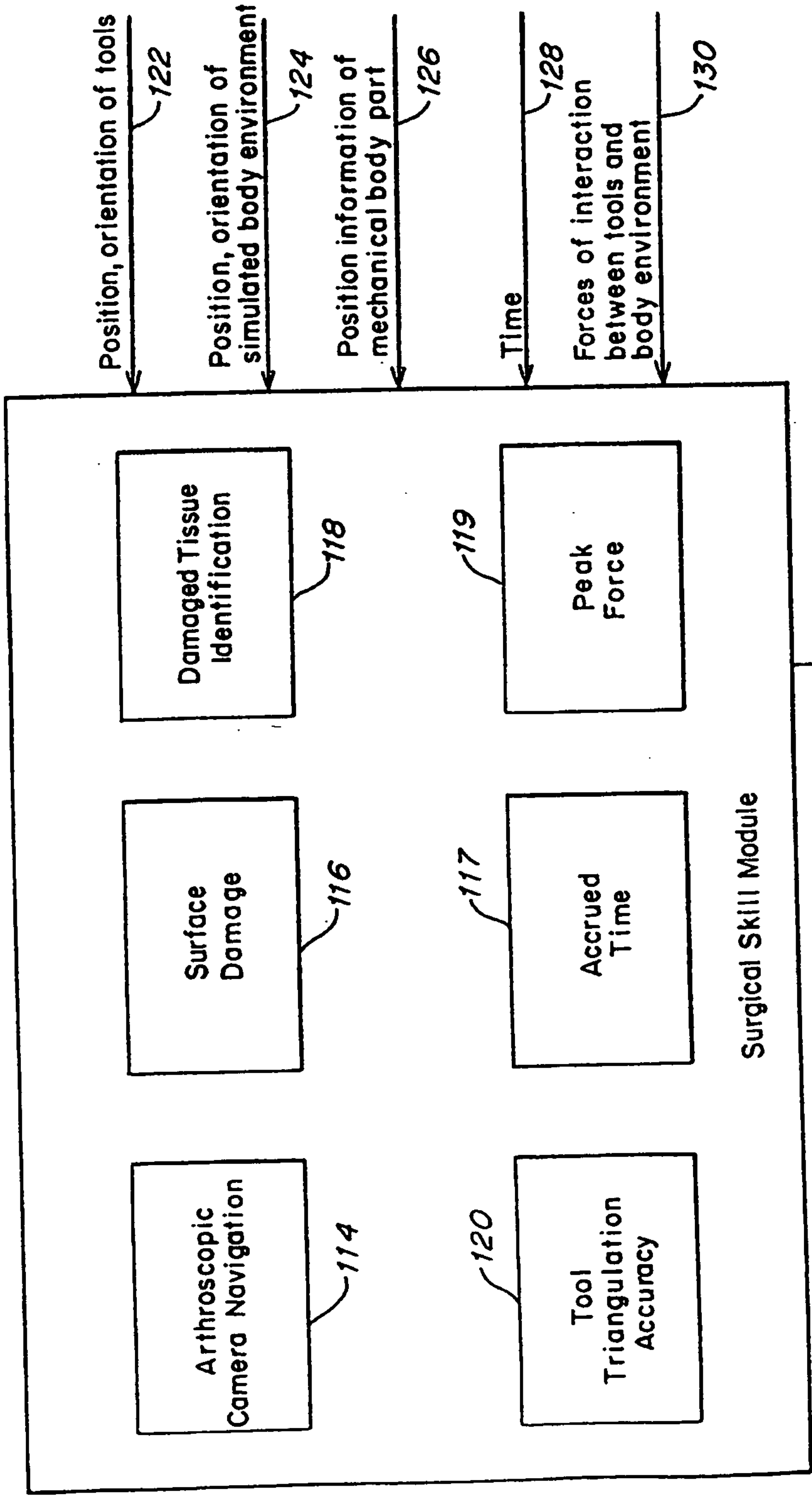
Position, orientation of tools
122
Position, orientation of simulated body environment
124
Position information of mechanical body part
126
Time
128
Forces of interaction between tools and body environment
130
Damaged Tissue Identification
118
Peak Force
119
Surface Damage
116
Accrued Time
117
Arthroscopic Camera Navigation
114
Tool Triangulation Accuracy
120
Surgical Skill Module
64

FIG. 10

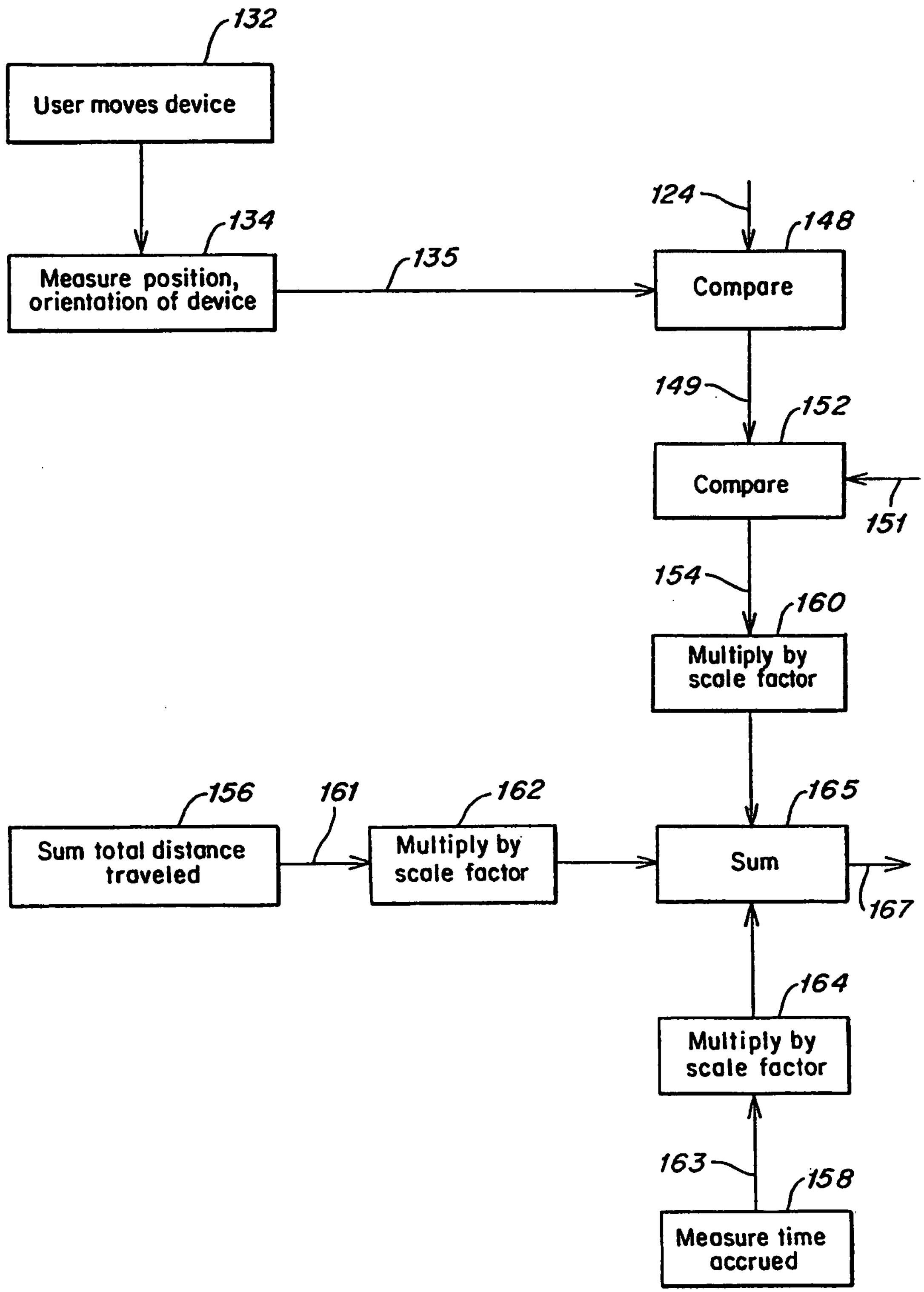
132
User moves device
134
Measure position, orientation of device
135
124
148
Compare
149
152
Compare
151
154
160
Multiply by scale factor
156
Sum total distance traveled
161
162
Multiply by scale factor
165
Sum
167
164
Multiply by scale factor
163
158
Measure time accrued

FIG. 11

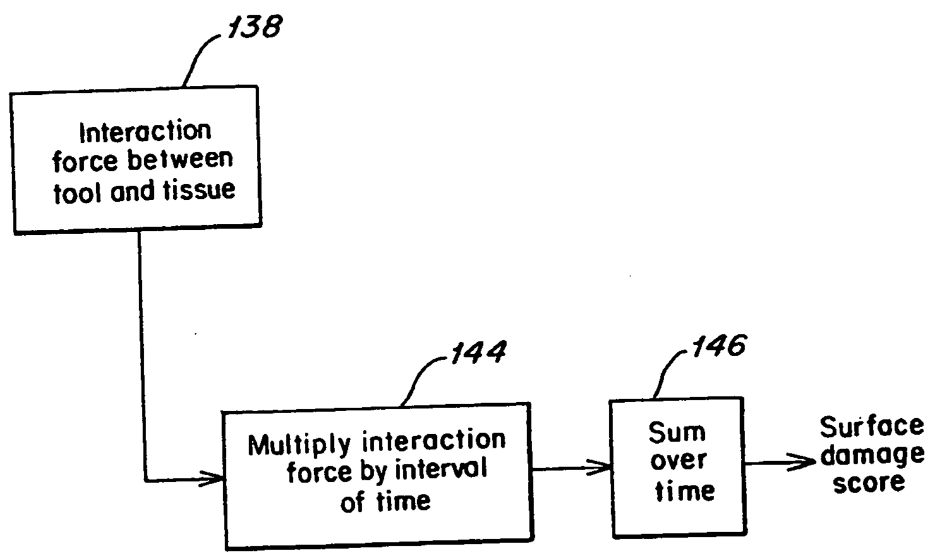
138
Interaction force between tool and tissue
144
Multiply interaction force by interval of time
146
Sum over time
Surface damage score

FIG. 12

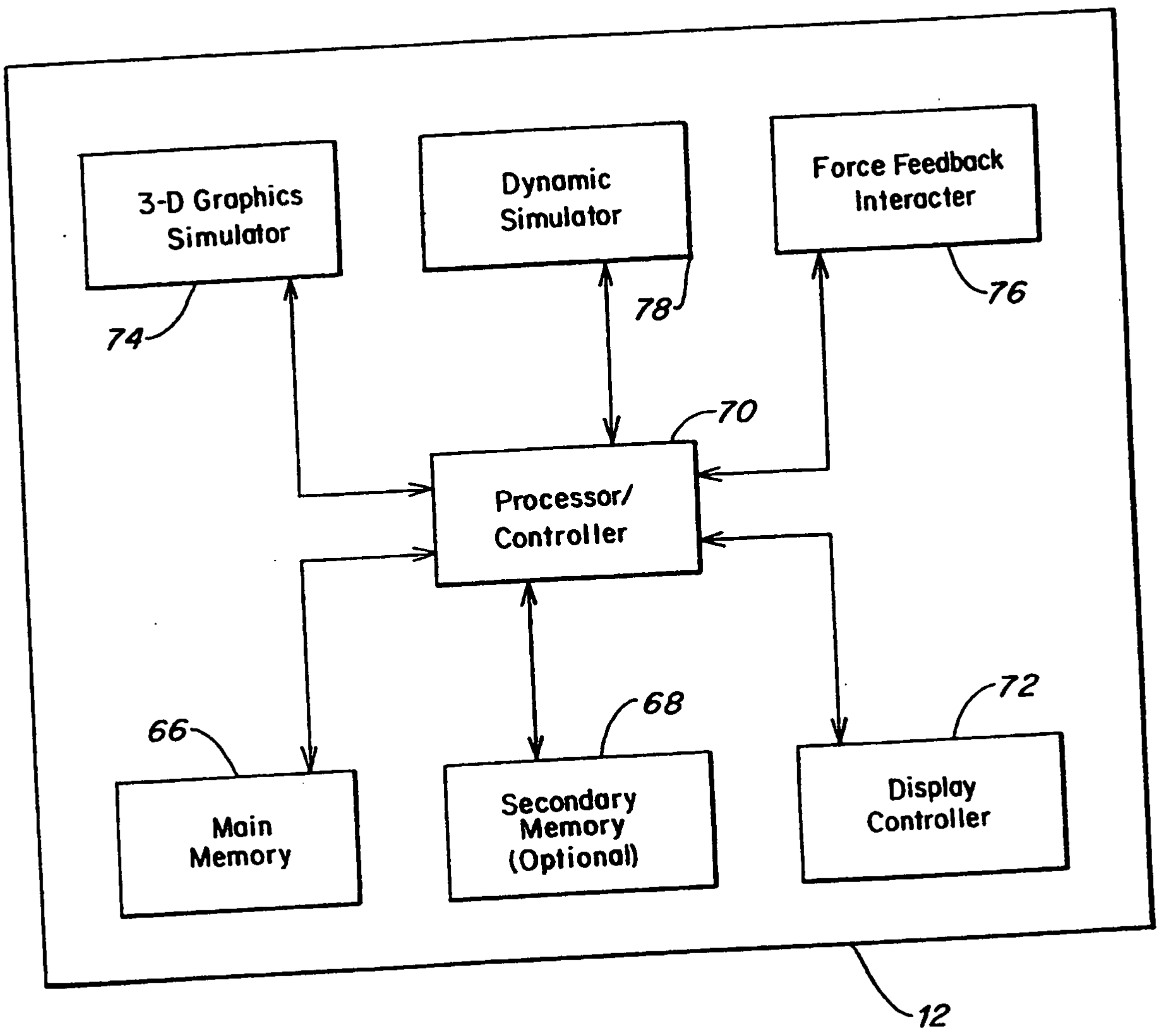
3-D Graphics Simulator
Dynamic Simulator
Force Feedback Interacter
74
78
76
70
Processor/ Controller
66
68
72
Main Memory
Secondary Memory (Optional)
Display Controller
12

Fig. 13

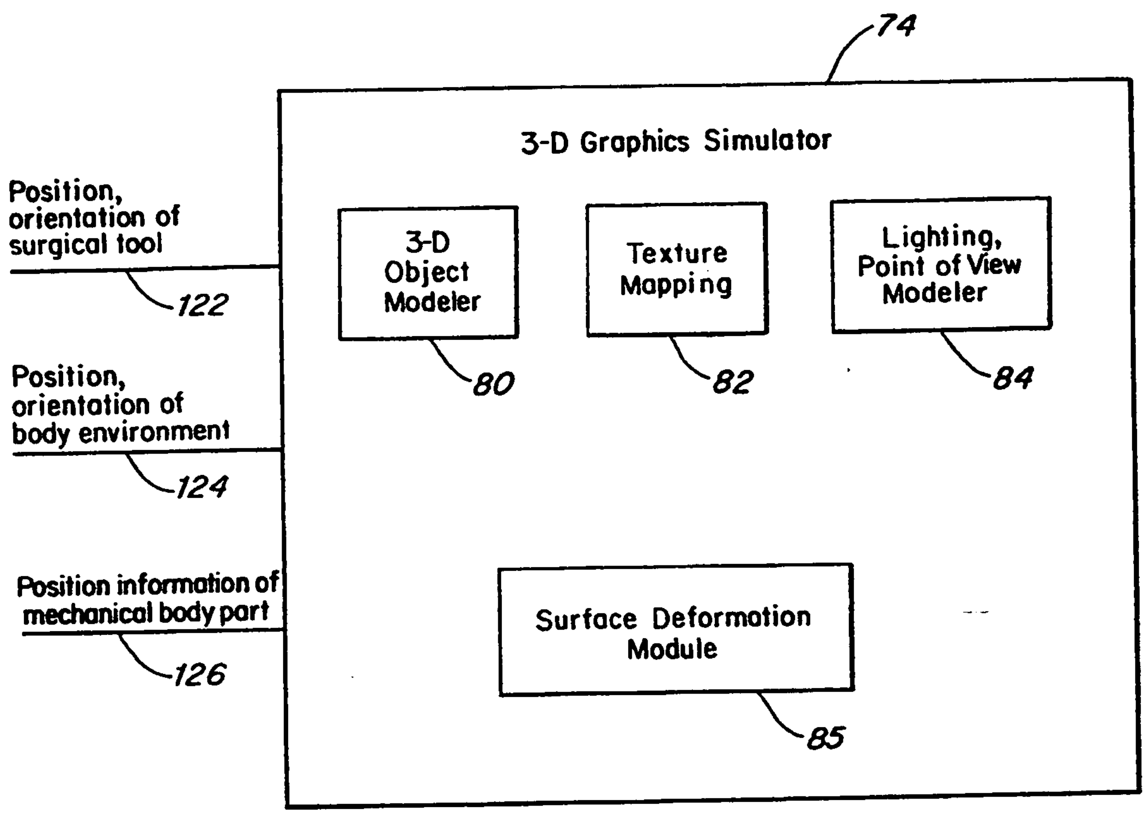
74
3-D Graphics Simulator
Position, orientation of surgical tool
122
3-D Object Modeler
80
Texture Mapping
82
Lighting, Point of View Modeler
84
Position, orientation of body environment
124
Position information of mechanical body part
126
Surface Deformation Module
85

Fig. 14

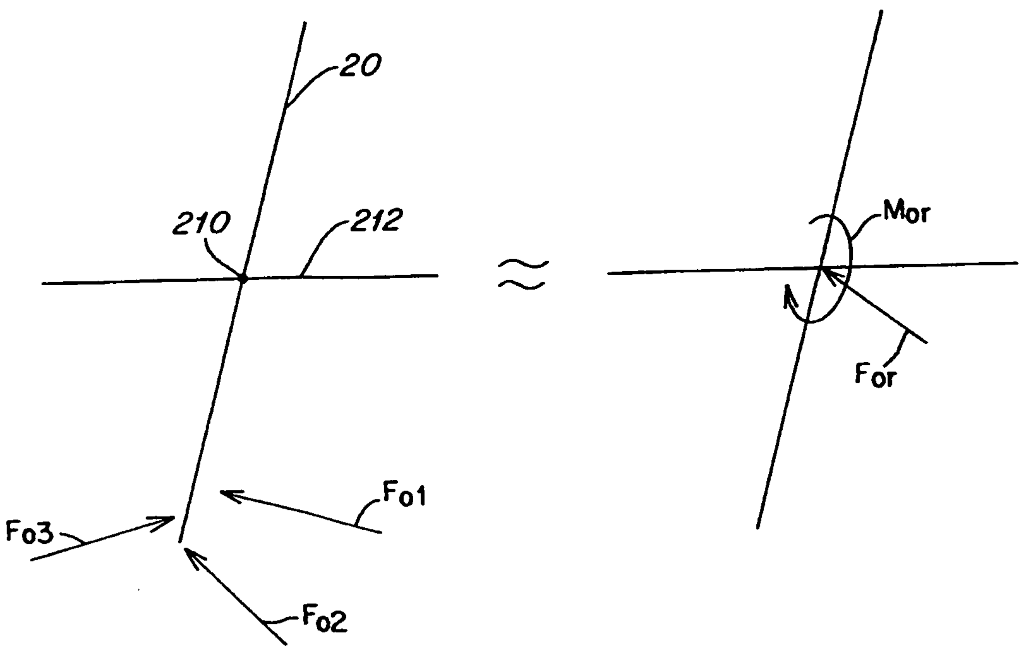

FIG. 15

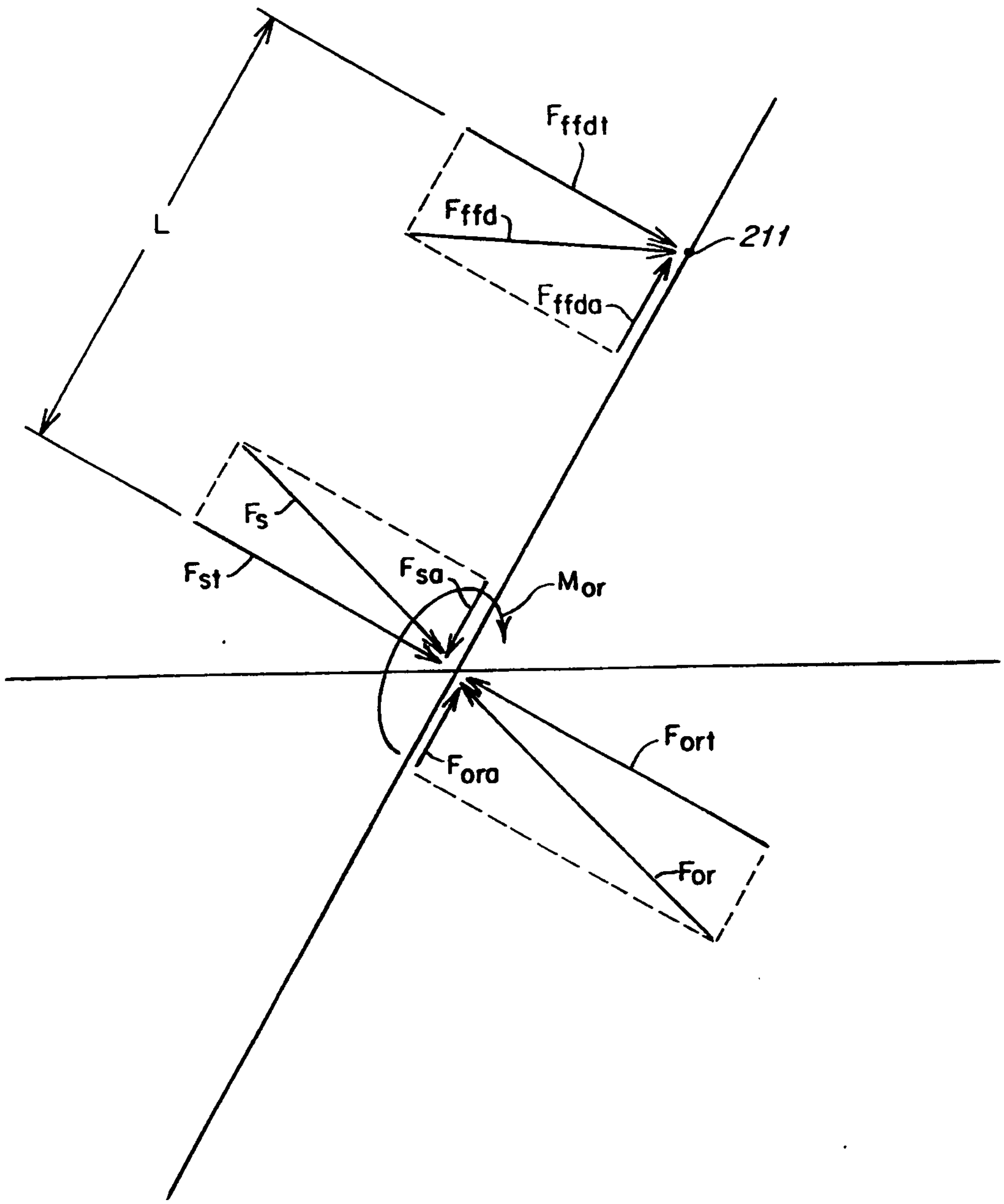

FIG. 16

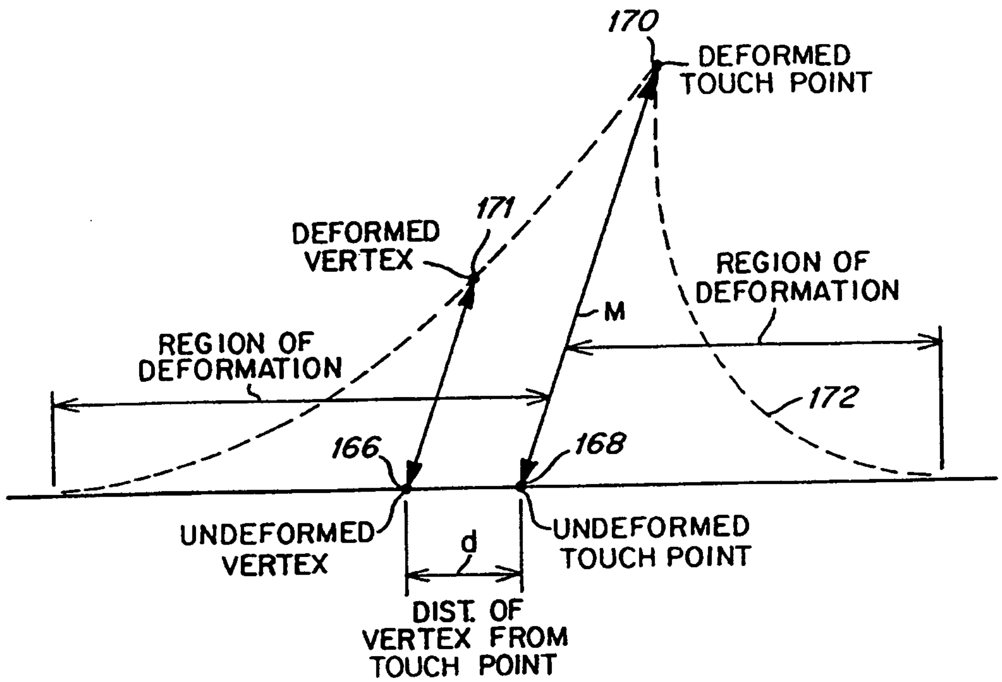

FIG. 17A

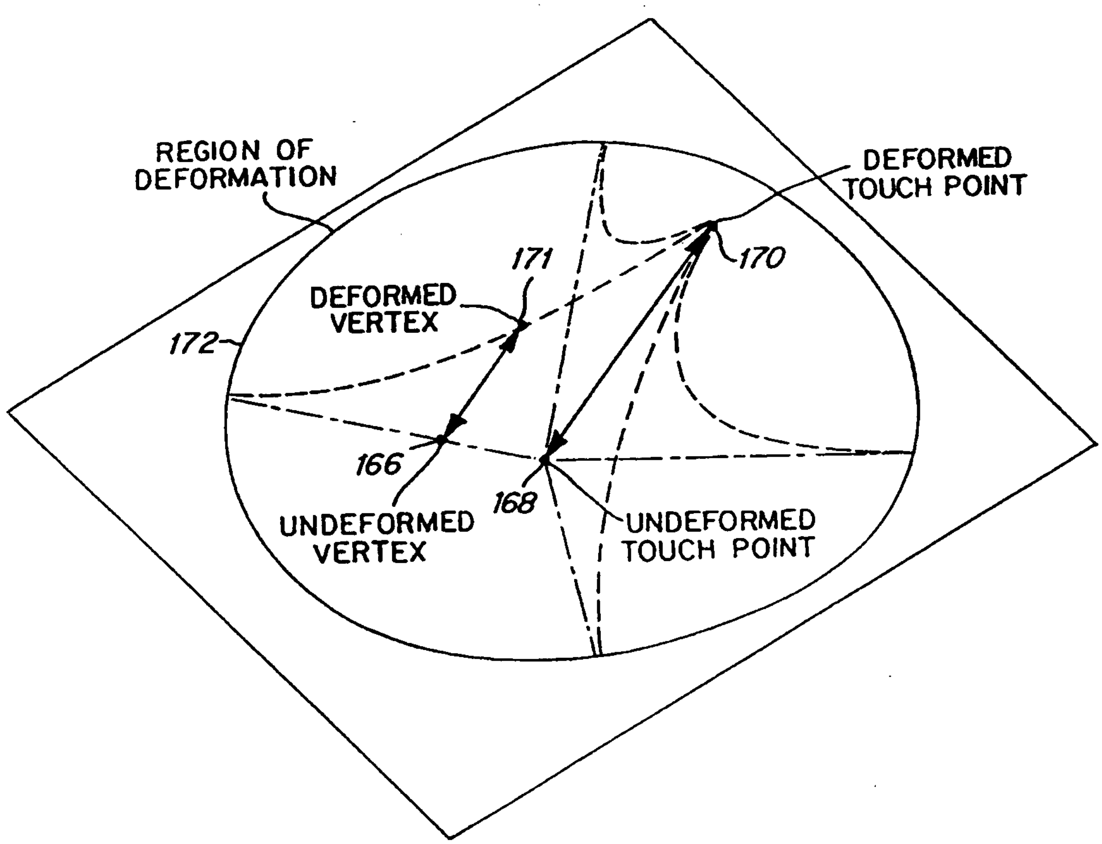

FIG. 17B

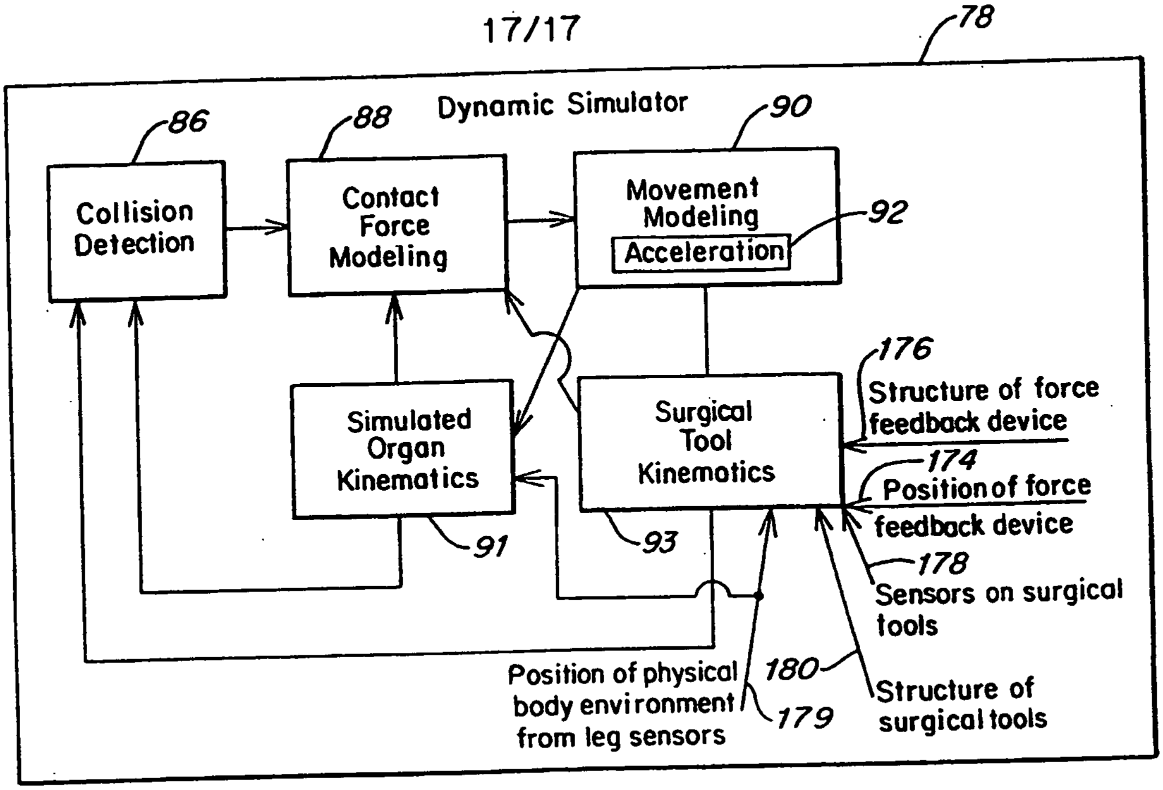
78
Dynamic Simulator
86
Collision Detection
88
Contact Force Modeling
90
Movement Modeling
Acceleration
92
Simulated Organ Kinematics
Surgical Tool Kinematics
176
Structure of force feedback device
174
Position of force feedback device
178
Sensors on surgical tools
91
93
Position of physical body environment from leg sensors
180
179
Structure of surgical tools

FIG. 18

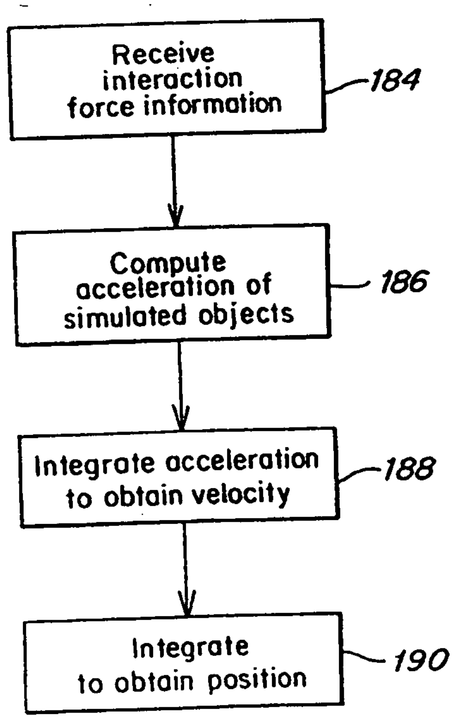
Receive interaction force information
184
Compute acceleration of simulated objects
186
Integrate acceleration to obtain velocity
188
Integrate to obtain position
190

FIG. 19

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/03617

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G09B23/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G09B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E	WO 99 17265 A (BOSTON DYNAMICS INC) 8 April 1999 see the whole document ---	1,3,4,6, 7,9-23, 25-27, 29-43
X	WO 96 30885 A (GILLIO ROBERT G) 3 October 1996 see page 11, line 22 - page 14, line 11 see page 18, line 28 - page 27, line 19; claims 1-48 --- -/--	1,3,4,6, 9-11, 13-15, 18,19, 23, 25-27, 29,30, 33,34,38

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search
18 June 1999

Date of mailing of the international search report
25/06/1999

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Fax: (+31-70) 340-3016

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Gorun, M

1

Inte onal Application No
PCT/US 99/03617

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 96 16389 A (STANEFF JOHN E JR ;MOORE ROBERT S (US); HARTHAN LEWIS JOHN III (US) 30 May 1996 see the whole document ---	1,3,4,6, 7,13-16, 20-23, 26,27, 33-36
A	WO 98 03954 A (COLORADO MEDICAL SIMULATORS IN) 29 January 1998 see the whole document ---	1,4,5,7, 8,23,25, 27,28
A	WO 97 33263 A (UNITED SURGICAL SERVICES LTD ;STROVER SHEILA MARGARET (GB); STROVE) 12 September 1997 see the whole document ---	1,2,6,23
A	US 4 433 961 A (CHANDLER EUGENE J) 28 February 1984 see the whole document -----	1,2,6,23

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intr   ional Application No
PCT/US 99/03617

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